A Comparison of Coalbed Methane Product Water Quality *Versus* Surface Water Quality in the Powder River Basin of Wyoming, and An Assessment of the Use of Standard Aquatic Toxicity Testing Organisms for Evaluating the Potential Effects of Coalbed Methane Product Waters

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Executive Summary

- Surface water quality differs significantly across the Powder River Basin (PRB). In particular, the Powder River is much more turbid and saline than the Tongue River. Also, the ionic compositions of the saline waters of the Powder River differ significantly from those of the Belle Fourche River and the Little Powder River.
- More data are required to conduct a thorough assessment of coalbed methane (CBM) product water quality, particularly from wells around Piney Creek and Clear Creek, the North and South Forks of the Powder River, Salt Creek, and the Tongue River.
- CBM product water conductivity, total dissolved solids, and alkalinity tend to increase from wells located southeast of the Belle Fourche River to wells located by the Powder River, east of the junction with Clear Creek.
- Product water quality can be highly variable among CBM wells. Therefore, the practice of using water samples from wells <20 miles apart to provide surrogate water quality for NPDES discharge permits can produce spurious results, even if the wells are located at the same depth and within the same geological formation. Our results indicate that well depth and geological formation are not strongly related to CBM product water quality.
- If WDEQ continues to allow CBM operators to use water samples from wells <20 miles away to provide surrogate water quality for NPDES discharge permits (even if the wells are drilled to the same depth and within the same geological formation), we recommend that follow-up chemical analyses of the water quality be submitted to WDEQ after the well is drilled -- to verify the appropriateness of that surrogate water quality data.
- Because surface water quality and CBM product water quality vary considerably across the PRB, CBM product water quality will have different impacts on each of the major waterways of the PRB.
- CBM product water from wells located east of the Powder River may tend to (1) increase sodium (Na^{+}) and bicarbonate (HCO_3^{-}) concentrations in much of the Powder River and (2) decrease chloride (Cl^{-}) and sulfate (SO_4^{2-}) concentrations and the water hardness (an index of the sum of the calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations).
- Limited information about CBM wells near the Tongue River suggests that product water might increase the salinity of the Tongue River.
- Because the Tongue River (to at least the Montana border), Piney Creek, Clear Creek (to several

km downstream from Piney Creek), Crazy Woman Creek (to approximately I-25), the North Fork of the Powder River, and the Middle Fork of the Powder River (to approximately I-25) provide relatively high-quality, low-salinity habitat for salmonid fishes, major increases in salinity and changes in ion ratios in those surface waters due to discharge of CBM product water might have significant impacts on recreational fisheries.

- Limited data about CBM product water from wells located around the Little Powder River suggest that product water is more "dilute" than the surface waters, except with regard to alkalinity. Therefore, product waters will tend to decrease Ca^{2+}, Mg^{2+} and SO_4^{2-} concentrations in the Little Powder River, but increase HCO_3^- concentrations.
- CBM product waters from wells located around the Belle Fourche River tend to be more "dilute" than surface waters, except with regard to alkalinity (mostly HCO_3^- at those pH values), Na^+, Cl^- and potassium (K^+) concentrations.
- The environmental cue of seasonal cycles in water quality (especially temperature) and discharge of surface waters of the PRB might be dampened by constant inflows of CBM product water having relatively constant quality and flow rates, thus potentially affecting resident aquatic biota.
- Analysis of surface water and CBM product water quality relative to lethality data for three commonly used aquatic toxicity testing species (*Daphnia magna, Ceriodaphnia dubia* and *Pimephales promelas*) indicates that at certain times, and in some locations, surface waters and undiluted CBM product waters might be acutely lethal to these organisms.
- We recommend that the tendency for CBM product waters to "dilute" some surface waters be considered just as potentially important to resident biota as is the tendency for CBM product waters to "salinate" other surface waters.
- We recommend that toxicity testing be conducted on receiving waters as well as whole effluents from CBM wells.
- We recommend that, if feasible, toxicity testing also be conducted using species resident in the surface waters of the PRB.
- Although toxicity testing will provide useful information about the impacts of CBM product water on aquatic communities, this information alone will not be sufficient to fully assess the ecological impacts. We recommend that alternatives to traditional laboratory-testing approaches, such as instream bioassessment, also be conducted.

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Introduction

The Powder River Basin (PRB; Fig. 1) is currently the site of a boom in coalbed methane (CBM) gas extraction in the state of Wyoming. To extract CBM gas, groundwater has to be pumped to the surface and either discharged or reinjected. There are concerns that discharged groundwater (also known as CBM product water) will negatively impact surface waters in the following ways:

1. discharge of large volumes of CBM product water will erode permanent and ephemeral streambeds into which they are discharged, and
2. the large volume and constant flow of saline CBM product water being discharged into existing waterways will significantly alter the hydrology, salinity and temperature of the receiving waters, thus altering the aquatic communities that inhabit those waters.

The impact of CBM product water discharges will vary depending partly on the magnitude of difference between product water quality and surface water quality. This report surveys historic and current data on surface water quality in the PRB gathered by the U.S. Geological Survey (USGS) and compares it to what is known about the quality of CBM product water. We also examine the water quality requirements of aquatic organisms, relevant to product water quality.

The report is organized into a comparison of surface water quality in the four major drainages of the PRB for several major water quality parameters. We then briefly discuss product water quality in the PRB according to major water quality parameters, focusing on evidence of regional trends. Next we compare surface water and product water quality of each major drainage. The report concludes with a discussion of the potential use of aquatic toxicity testing organisms such as *Daphnia* species, *Ceriodaphnia dubia*, and fathead minnows *Pimephales promelas* for evaluating toxicological effects of discharges of CBM product water to surface waters.

Surface Water Quality

The major waterways in the PRB are the Powder River (PR) and its tributaries (including the Little Powder River (Little PR)), Tongue R in the northwest, and the Belle Fourche River (Belle Fourche R) in the east (Fig. 2).

Surface Water Quality Data Sources

We have summarized surface water quality data from the National Water Information System (NWIS; http://water.usgs.gov/nwis) to characterize the typical range of water quality in these waterways. The data were collected from 1951 until 1999, and the main source is the United States Geological Survey (USGS; Tables 1-2 and Fig. 3). At selected sites the USGS has maintained instruments that continuously record physical and chemical characteristics of the water including parameters such as pH, specific conductivity, temperature and dissolved oxygen. Some of the data are from discrete samples collected for a variety of projects, ranging from national programs to studies in small watersheds. Because the data come from a variety of sources, we cannot guarantee the quality of the data. Also, some of the data were collected after significant development projects (e.g., Keyhole Reservoir), irrigation, and some CBM development had occurred and altered the nature of the PRB waterways. Nonetheless, the NWIS database is a useful starting point to begin to understand the characteristics of the major waterways of the PRB and the potential impact of CBM product waters.

Surface Water Quality Overview

These waterways vary significantly in their typical water quality, both within a drainage, from the upstream headwaters to downstream, and across the various major drainages of the PRB (Table 1 and Figs. 4-17). The water quality (including discharge volumes) of the PRB also varies significantly over time (e.g., discharge varies from 2 to 17,800 ft^3/s in the downstream PR), usually on a seasonal basis (see Appendix A). In attempting to summarize these surface water quality data for the purposes of discussion and relate them to product water quality, we have simplified the data somewhat and used median values to characterize overall water quality. We have also reported minimum and maximum water quality parameters to capture the range of variation possible in each waterway. These water quality parameters vary according to seasonal cycles (Appendix A) that are integral to the biotic community dependent on the waterways of the PRB (Allan 1996). One of the most important differences between product water quality and surface water quality is the lack of seasonality in product water quality. In particular, the constant flow of water from CBM wells could tend to stabilize surface water flow regimes, which could have a negative effect on fish species native to the PRB. Variability of flow is a characteristic that tends to favor the persistence of fish species native to the PRB over non-native fish species (Cross et al. 1985, Sanders et al. 1993, Rabeni 1996).

Surface Water Quality in the Four Major Drainages of the Powder River Basin

Median concentrations of anions (HCO_3^-, CO_3^{2-}, Cl^-, SO_4^{2-}, OH^-) and cations (Ca^{2+}, Mg^{2+}, K^+, Na^+, H^+) are listed in the traditional concentrations of mg/L in Table 1. To allow more valid comparisons of the relative contributions of those ions to the total ionic strength of the waters, we calculated the median molar concentrations of those ions (Table 3) and their molar percentages (Table 4). We also converted those molar concentrations to mEq/L to calculate ion balances. For all of the surface waters, the percent difference between the sum of the median mEq/L for the anions and the sum of the median mEq/L for the cations was <7% (results not shown). This is excellent agreement for the median concentrations, considering that a 5% difference is considered good agreement for analyses within a single water sample.

Surface Waters: Specific Conductance and Salinity

The downstream PR has extremely high specific conductance varying from 70 to 6500 μS/cm at 25°C, with a median conductance of 2480 μS/cm at 25°C (Fig. 7 and Table 1). This indicates the presence of high concentrations of anions and cations in the water, and is commonly understood as high salinity water. More detailed analysis shows that this high conductance is probably due to high sodium (Na^+; median, 350 mg/L), chloride (Cl^-; median, 210 mg/L) and sulfate (SO_4^{2-}; median, 810 mg/L) concentrations (Figs. 6, 14 and 15). Some of the high conductance is also due to moderate-to-high concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}; Figs. 5 and 11). It is important to realize that although this water can correctly be called saline, its composition differs from typical seawater. In seawater, salinity is due to high concentrations of Na^+ and Cl^-, and relatively low concentrations of SO_4^{2-}, Mg^{2+}, Ca^{2+}, potassium (K^+), and bicarbonate (HCO_3^-) ions (Sumich 1999).

Water quality in the upstream PR, Crazy Woman Creek, Salt Creek and the South Fork PR is similar to the downstream PR, with high salinity attributable mostly to Na^+, Cl^- and SO_4^{2-} ions, except for Crazy Woman Creek, which has relatively low concentrations of Na^+ and Cl^- ions. The northwestern portion of the PR watershed includes the upstream and downstream Clear Creek sites and Piney Creek. In these tributaries of the PR, the specific conductance tends to be lower at the upstream sites (Piney Creek, median 640 μS/cm at 25°C; upstream Clear Creek, median 825 μS/cm at 25°C). Much of the high conductance is attributable to SO_4^{2-} ions and low-to-moderate concentrations of Ca^{2+} and Mg^{2+}. In contrast to the southeastern tributaries of the PR, the median Cl^- concentrations in the northwestern tributaries are relatively low (medians, 2.4-4.2 mg/L).

The Tongue R has relatively low conductance in its upstream (median, 252 μS/cm at 25°C) and downstream (median, 450 μS/cm at 25°C) reaches before its confluence with Goose Creek. Median Na^+ concentrations were only 1.6 to 15 mg/L, but the maximum concentration was 240 mg/L. Median Ca^{2+}, Mg^{2+} and Cl^- concentrations were all relatively low compared to the PR. Goose Creek tends to have higher conductivity (median 700 μS/cm at 25°C) than the Tongue R, probably due mostly to high concentrations of SO_4^{2-} ions (median, 150 mg/L) and moderate concentrations of Na^+, Ca^{2+}, and Mg^{2+} ions.

Both the Little PR (median, 2610 μS/cm at 25°C) and the Belle Fourche R (median, 3800 μS/cm at 25°C) in the eastern portion of the PRB have consistently high conductance. Although over 82 measurements were taken between 1975 and 1983, the minimum recorded conductance in both rivers was 1100 μS/cm at 25°C. Both rivers are characterized by relatively high concentrations of SO_4^{2-} (range, 510-5400 mg/L) and K^+ (range, 3-56 mg/L) (Fig. 13) and moderately high concentrations of Na^+, Ca^{2+}, and Mg^{2+}.

Surface Waters: Hardness

Hardness is the sum of the divalent cation concentrations (usually mostly Ca^{2+} and Mg^{2+} ions) in water (APHA et al. 1995), expressed as the concentration of $CaCO_3$ (mg/L) that, when added to distilled water, would produce the same hardness as the water sample. Surface waters are generally considered to be "hard" if their hardness is >100 mg/L as $CaCO_3$ (Hem 1985). Therefore, all the waters of the PRB have moderate to high hardness. The trends in hardness of the surface waters of the PRB roughly follow those of conductivity, but are less extreme. In summary, the waters of the mainstem PR and its southeastern tributaries, including the South Fork, Salt Creek and Crazy Woman Creek have high hardness (medians, $\geq$400 mg/L as $CaCO_3$; Fig. 10 and Table 1). The Clear Creek/Piney Creek branch of the PR tends to have slightly lower hardness, especially in the two upstream locations (medians, 260-480 mg/L as $CaCO_3$). Among the 13 sites we surveyed, the upstream and downstream Tongue R sites and its Goose Creek tributary had the lowest median hardness values (range, 130-340 mg/L as $CaCO_3$), which is consistent with the generally lower salinity of these northwestern PRB waters. Both the Little PR and the Belle Fourche R have the highest median hardness values (1300 and 1500 mg/L as $CaCO_3$, respectively) and highest maximum hardness values (3300 and 3500 mg/L as $CaCO_3$, respectively) of all of the PRB sites.

Surface Waters: Acid Neutralizing Capacity (Alkalinity)

Acid neutralizing capacity (ANC) refers to the alkalinity of water, and is a sum of the concentrations of the HCO_3^-, CO_3^{2-} and OH^- ions in water, balanced against the "acidity" (or hydrogen ion concentration) of that water. Like hardness, alkalinity is expressed as mg/L as $CaCO_3$. Because median pH in the PRB waterways varied from 7.9 to 8.2 (Fig. 12) and alkalinity was ≥129 mg/L as $CaCO_3$ (Fig. 4), most of the alkalinity will be attributable to HCO_3^- ions.

In terms of alkalinity, the most notable waterway of the PR is Salt Creek, where the median alkalinity was 618 mg/L as $CaCO_3$ (range, 150-1160 mg/L as $CaCO_3$; Fig. 4 and Table 1). In the remainder of the PR drainage, the Tongue R drainage, the Little PR, and the Belle Fourche R, median alkalinity was between 129 and 290 mg/L as $CaCO_3$. The range of minimum and maximum alkalinity values is also fairly similar across the PRB, falling within 20 to 410 mg/L as $CaCO_3$, except for the two PR stations that ranged up to 640 mg/L as $CaCO_3$, probably under the influence of Salt Creek (Table 1).

Surface Waters: pH (standard units)

Median pH, or acidity, of all PRB waterways that we surveyed was between 7.9 and 8.2 standard pH units (Fig. 12 and Table 1). The lowest pH readings were taken in the upstream PR (minimum, pH 6.4), while most other waterways had a minimum pH between 6.8 and 7.4. The maximum pH (9.2) was recorded in Piney Creek in the western portion of the PR drainage.

Surface Waters: Temperature

Water temperatures vary in the PRB from minima of 0ºC (32ºF) to maxima of 21 to 32ºC (70-90ºF; Table 1). Changes in water temperature are mostly due to seasonal variation in weather.

Overall, the Belle Fourche R (median, 13.5ºC), the PR and its southern tributaries (the South Fork, Salt Creek, and Crazy Woman Creek, medians 9.75-12.5ºC) tended to have the highest median water temperatures compared to upstream and downstream Clear Creek (medians, 8.75 and 10ºC) and Piney Creek (median, 9.75ºC; Fig. 16). The Tongue R (upstream and downstream), Goose Creek (medians, 5.0-9.0ºC) and the Little PR (median, 6ºC) had the lowest median water temperatures.

Water temperatures tend to increase from upstream headwaters toward downstream reaches, and seasonal changes in water temperature are an important environmental cue for many aquatic organisms (Allan 1996). The PRB waterways support salmonid (members of the fish family that includes trout and salmon) species and many native, non-salmonid species of Wyoming (Hubert 1993). The major stream and river reaches containing salmonids are located on the western side of the PRB, including the Tongue River (to at least the Montana border), Piney Creek, Clear Creek (to several km downstream from Piney Creek), Crazy Woman Creek (to approximately I-25), the North Fork of the Powder River, and the Middle Fork of the Powder River (to approximately I-25). The downstream distributions of salmonids in the PRB are thought to be mostly controlled by high temperatures and/or high turbidity levels that exceed the fishes' tolerance levels (personal communication, Robert McDowell, Wyoming Department of Game and Fish).

Surface Waters: Dissolved Oxygen

Dissolved oxygen (DO) concentrations are generally high across the PRB (medians, 8.3-10.6 mg/L), although some waters of the PR and the Little PR have minimum DO concentrations much less than 5 mg/L (Fig. 9 and Table 1). Dissolved oxygen concentrations less than 5 mg/L are too low to sustain many species of fish, especially salmonids (Piper et al. 1982). However, DO is influenced by physical factors such as riffles and wind disturbance that can reoxygenate the water. Therefore, even though low DO concentrations were recorded at some of the USGS sampling sites, "refuges" of higher DO concentrations might have been in close proximity to these stations.

Salt Creek had the lowest DO concentrations of 0.5 mg/L; and, perhaps under the influence of Salt Creek, both the upstream and downstream stations of the PR (both stations located downstream of Salt Creek) had minimum DO concentrations of 2.9 to 4.5 mg/L. The Little PR had a DO minimum of 3.4 mg/L. The western tributaries of the PR, Piney Creek and Clear Creek all had DO minima well above 5 mg/L (range, 6.6-8.0 mg/L), as did the Belle Fourche R. The Tongue R had high DO concentrations at all times (min.-max. range, 7.6-13.6 mg/L); but its tributary, Goose Creek, had a slightly lower minimum of 5.6 mg/L.

Surface Waters: Turbidity

The PR and its southern tributaries (the South Fork, Salt Creek, and Crazy Woman Creek) are characterized by turbid waters (medians, 55-475 Jackson Candle Units (JCU); Fig. 17 and Table 1). Except for the South Fork of the PR, the minimum turbidity in these waterways was $\geq$10 JCU, and the maximum turbidity was 100 to 8000 JCU. The western tributaries of the PR (Clear Creek and Piney Creek) generally have much lower turbidity, with medians from 2 to 9 JCU. However, the downstream Clear Creek station had a maximum turbidity of 500 JCU. The Tongue R, Little PR, and Belle Fourche R all had median turbidities of $\leq$8 JCU and maxima of 20 to 100 JCU.

Surface Water Quality Summary

This brief survey of the waterways of the PRB indicates that the water quality of the PR is not the same as the water quality of the Tongue R, the Little PR or the Belle Fourche R. For example, the waters of the PR close to the Wyoming-Montana border in the north-central portion of the PRB are relatively saline (median conductivity, 2480 μS/cm at 25°C) and turbid (median turbidity, 475 JCUs), whereas the downstream Tongue R in the northwest portion of the PRB is much less saline (median conductivity, 450 μS/cm at 25°C) and less turbid (median turbidity, 4 JCUs; Table 1). Even within the PR drainage, the water quality of Clear Creek and its tributary Piney Creek is different in some important aspects to the mainstem PR and its southern tributaries.

Within the PR drainage, the southern portion (South Fork PR, Salt Creek and Crazy Woman Creek) can be considered turbid, saline and subject to extreme variations in water temperature and DO content. The high conductivity of these waters is due mostly to high concentrations of Na^{+}, Ca^{2+}, Cl^{-} and SO_4^{2-}.

In the western tributaries of the PR (Clear Creek and Piney Creek), DO concentrations are more stable and the water is less turbid. Salinity also tends to be lower in these waters, due mostly to considerably lower Na^{+}, Cl^{-} and SO_4^{2-} concentrations than the mainstem PR.

The Tongue R and its tributaries tend to have consistently high DO concentrations and relatively low water temperatures, low salinity and low turbidity.

The Little PR and Belle Fourche R in the eastern portion of the PRB have unique water quality characteristics compared to the western waters of the PRB. Both rivers tend to have relatively high salinity waters containing high concentrations of Na^{+}, Ca^{2+}, Mg^{2+}, and SO_4^{2-}. Compared to the other waters of the PRB, both rivers had slightly higher concentrations of K^{+}; and compared to the PR, both rivers had much lower concentrations of Cl^{-}. Turbidity in both rivers tends to be low. On occasion, the Little PR had low DO concentrations, whereas DO concentrations of the Belle Fourche R were relatively high.

CBM Product Water Quality in the Powder River Basin

Conventional wisdom is that product water quality differs significantly across the PRB. The general trend is thought to range from so-called "drinking-water quality" in the southeast portion of the basin to more saline, non-potable waters in the northwest portion of the basin. Below we test that conventional wisdom using four datasets from a variety of sources.

Product Water Databases

We obtained data about CBM product waters from the following four sources:

Dataset A: Rice et al. (2000),

Dataset B: Petroleum Association of Wyoming (2001),

Dataset C: WDEQ NPDES permits through May 2001, and

Dataset D: WDEQ-funded WET studies (Forbes et al. 2001).

Dataset A (Rice et al. 2000) describes water collected directly from wellheads and not mixed with surface water. Datasets B and C describe water samples taken at the "designated discharge point" for a National Pollutant Discharge Elimination System (NPDES) permit granted by the Wyoming Department of Environmental Quality (WDEQ) and presumably collected in accordance with NPDES permit guidelines. Dataset D is from water samples collected at wellheads by WDEQ field staff for a whole-effluent toxicity (WET) testing project conducted in collaboration with University of Wyoming researchers (Forbes et al. 2001). Although Rice et al. (2000) provided the most comprehensive summary of data from 47 wells in the eastern PRB and speculated on the causes of the unique chemistry of these CBM product waters, they did not interpret the water quality data in terms of interactions with the aquatic ecosystems of the PRB. We had three objectives for interpreting these data:

1. Obtain water quality information from wells across the basin and from different geological formations, to characterize the range of water quality produced by CBM wells.
2. Compare CBM product waters to surface waters in the basin, to determine if there are significant differences in water quality and important regional trends.
3. Compare surface water and CBM product water quality to toxicity data for three standard test organisms (fathead minnows *Pimephales promelas*, *Daphnia* spp., and *Ceriodaphnia dubia*).

Product Water Locations

1. Rice et al. (2000) obtained data from wells east and southeast of the PR (e.g., circles in Figs. 18, 32, 57 and 71). Many of the wells were located around the Belle Fourche R (Fig. 71).
2. Petroleum Association of Wyoming initial discharge permit data from 15 wells within Campbell county or westward were obtained from a dataset of 37 wells (e.g., crosses in Figs. 32, 46 and 57). The remaining wells were outside our area of study.
3. We obtained six datasets from the WDEQ NPDES permits. Although we originally collected 22 datasets from a selection of well locations in the region, we later discovered that they referred back to only six water samples (e.g., Figs. 32, 46 and 57).
4. Data from six CBM product water samples provided to the University of Wyoming by WDEQ were obtained from the Tongue R, PR, Little PR, and Belle Fourche R drainages (e.g., Figs. 18, 32, 46, 57 and 71).

Product Water Quality in the Four Major Drainages of the Powder River Basin

Product Waters: Conductivity

Conductivity of product waters varied from to 470-5300 μS/cm in the four datasets (Figs. 22, 36, 49, 61 and 75). There was a regional trend of conductivity increasing from <1000 μS/cm southeast of the Belle Fourche R to approximately 3000 μS/cm immediately east of the confluence of the PR with Clear Creek. Conductivity of product water was also relatively high near the Tongue R (1630-2180 μS/cm), although few data were available.

Conductivity increases as the temperature of the water sample increases (Hem 1985). In dataset A, conductivity was measured at 20ºC; in dataset B, it was measured at 25ºC; in dataset C, temperature was not reported; and in dataset D, it was measured at a range of temperatures (13-26ºC). The 5ºC between datasets A and B will result in a $\geq$10% difference in conductivity (Hem 1985).

Product Waters: Total Dissolved Solids

TDS concentrations ranged from 270 to 2390 mg/L in datasets A and B, which were mostly from the region east of the PR and in the southeast around the Belle Fourche R (Figs. 31, 45, 56, 70 and 84). There was a regional trend for low TDS in the southeast (400-500 mg/L) increasing to high TDS (985-2280 mg/L) east of the PR. These trends mirror those in the conductivity data.

Rice et al. (2000) concluded that the generally high TDS and high conductivity of their CBM product waters was due mostly to high Na^+ and HCO_3^- concentrations (Figs. 28, 42, 67 and 81). Similarly, the Petroleum Association of Wyoming samples (dataset B) were dominated by Na^+ and HCO_3^- (Figs. 28, 42 and 53). Maximum Na^+ and HCO_3^- concentrations in the two datasets were 905 and 1155 mg/L, respectively. Bicarbonate concentrations were reported separately in only one of 51 samples (data not shown), but because alkalinity ranged from 290 to 2320 mg/L as $CaCO_3$ and pH was ≥6.8 and ≤9.0, HCO_3^- probably was the dominant anion in those waters. Maximum Cl^- was 64 mg/L (Figs. 21, 35, 48, 60 and 74), and maximum SO_4^{2-} was 28 mg/L (Figs. 29, 43, 54, 68 and 82). Insufficient data were provided in the NPDES permits (dataset C) to determine the major anions in these water samples; however, unlike the samples taken by Rice et al. (2000), Cl^- (1260 mg/L) and SO_4^{2-} (761 mg/L) concentrations were very high in some NPDES samples. Major ions were not analyzed in the WDEQ WET samples (dataset D). TDS was not measured for the WDEQ NPDES permits (dataset C), or in the WDEQ WET data (dataset D).

Product Waters: pH, Alkalinity and Hardness

Product water pH varied from 6.8 to 9.0 (Figs. 26, 40, 52, 65 and 79). There were no obvious regional trends in pH, although all four product waters from near the Tongue R had pH >8.0.

Alkalinity and hardness were much more variable than pH, but almost all product waters were hard and alkaline (i.e., >100 mg/L as $CaCO_3$, for each parameter; Figs. 18, 24, 32, 38, 46, 50, 57, 63, 71 and 77). Rice et al. (2000) found alkalinity varied from 290 to 2320 mg/L as $CaCO_3$, tending to increase from wells in the southeast by the Belle Fourche R to the northwest near the PR. However, one product water near Dead Horse Creek (south PR) had the highest alkalinity (2320 mg/L as $CaCO_3$).

Like alkalinity, Na^+ concentrations in product waters tended to increase from the southeast to the northwest portions of the PRB (Figs. 28, 42, 53, 67 and 81). Hardness did not exhibit the same trend (Figs. 24, 38, 50, 63 and 77).

Product Waters: Ammonia

Ammonia concentrations in product waters from the area around Belle Fourche R up to east of the PR ranged from 1.1 to 5.3 mg NH_4^+/L (Rice et al. 2000; Figs. 19, 33, 58 and 72). There were no obvious regional trends in these data. No ammonia data were available for wells around the

Tongue River. To interpret NH_4^+ concentrations in terms of concentrations of the more toxic unionized NH_3 species, we used the temperature and pH of the product water to calculate percentages of toxic unionized NH_3 (Piper et al. 1982). In 30 of 47 samples, unionized NH_3 concentrations were >0.012 mg/L, which is the threshold for chronic toxicity to salmonid growth (Piper et al. 1982); and 13 samples exceed the threshold of 0.02 mg NH_3/L NH_3 recommended by the U.S. Environmental Protection Agency (USEPA 1976) for protection of salmonids in freshwater. To predict the increase in unionized ammonia concentrations in a receiving water due to the discharge of a specific CBM product water, the temperature and pH of the receiving water and the mixing ratio of the discharge and receiving waters would have to be known.

Ammonia was not measured in the WDEQ NPDES or WDEQ WET samples. Only one ammonia concentration was measured in the WDEQ initial discharge samples (1.1 mg/L of total ammonia as N, which is equivalent to 1.3 mg/L of total ammonia as NH_3).

Product Waters: Temperature and Dissolved Oxygen

We only have product-water temperature data from two sources: datasets A and D. Product water temperatures ranged from 11.7 to 28.7°C, and there were no obvious regional trends (Figs. 30, 44, 55, 69 and 83). No information is available to determine whether product water temperatures change seasonally, although groundwater usually discharges at a relatively constant temperature (Piper et al. 1982). Dissolved oxygen concentration was not reported for any of the product waters.

Product Waters: Influence of Well Depth and Geological Formation

Although the quality of CBM product waters varies widely across the PRB, product waters in close proximity to each other have been assumed to have similar composition if they are pumped from approximately the same depth in the same geological formation. For example, in order to obtain a NPDES permit from WDEQ, operators may use a water sample from a well within 20 miles of the proposed CBM well as a surrogate for the proposed well's water quality -- as long as the surrogate well is from the same geological formation and the same depth.

We tested the idea that the well depth and geological formation from which product water originates strongly influence water quality. When examining product waters collectively, neither depth nor geological formation was a good predictor of product water temperature, alkalinity, hardness, conductivity or concentrations of total dissolved solids, Ca^{2+}, Mg^+, SO_4^{2-}, Cl^-, K^+ or Na^+

ions (Figs. 85-87). Although temperature, hardness, Ca^{2+} and SO_4^{2-} concentrations tended to be related to depth for product waters originating from the Canyon Formation, there was insufficient data to fully evaluate these weak trends. Additionally, there was insufficient data to fully assess the relationship between depth and water quality for product water originating from the Wyodak, Pawnee, Fort Union, Cook and Big George Formations.

Even if a strong relationship existed between water quality and the depth and geological formation of wells, the WDEQ requirements for the use of surrogate water quality data do not always appear to be met in practice. For example, we found that 8 of 14 wells for which we had NPDES permit data and that had relied on surrogate-well data were >20 miles from their reference well. There was no information available to assess whether the surrogate well water had been collected from the same depth and geological formation as the wells to which they were applied. Rice et al. (2000) explained that there is a great deal of confusion about the naming of geological formations in the region, which further increases the difficulty of determining whether samples and wells are from/in the same formation.

Finally, reliance on the close proximity of two wells can lead to spurious conclusions about the water quality. For example, alkalinity was 947 and 2320 mg/L as $CaCO_3$ in product water from two wells <8 miles from each other (Fig. 32); sulfate concentrations were 0.01, 40 and 761 at 3 wells <10 miles from one another (Fig.43); and TDS concentrations varied between 730 and 1120 mg/L in 5 wells located <4 miles apart (Fig. 84). Thus, the quality of CBM product water can be highly variable over short distances (miles).

Product Water Quality Summary and Recommendations

- Our findings support the conventional wisdom that, in general, CBM product waters range from less saline in the southeastern portion of the PRB to more saline, non-potable waters in the northwestern portion of the PRB. However, we can neither support nor reject the purported "drinking water quality" of the less saline product waters in the southeastern portion of the basin.
- Product water quality can be highly variable among CBM wells. Therefore, the practice of using water samples from wells <20 miles apart, drilled to the same depth and within the same geological formation, to provide surrogate water quality for NPDES discharge permits does not always appear to provide reliable predictions of CBM product water quality. Our results indicate that well depth and geological formation are not strongly related to CBM product water quality.

- If WDEQ continues to allow CBM operators to use water samples from wells <20 miles away to provide surrogate water quality for NPDES discharge permits (even if the wells are drilled to the same depth and within the same geological formation), we recommend that follow-up chemical analyses of the water quality be submitted to WDEQ after the well is drilled -- to verify the appropriateness of that surrogate water quality data.

Product Water Quality *Versus* Surface Water Quality

Product Water *Versus* Surface Water: Mainstem Powder River

Based on median values, the main difference between surface waters and CBM product waters in the region of the mainstem PR is that the main ions in product waters usually are Na^+ (range, 409-994 mg/L) and HCO_3^- (range of alkalinity values, 580-2440 mg/L as $CaCO_3$), whereas the main ions in the surface waters are Na^+ (medians, 350 mg/L), Cl^- (medians, 210-220 mg/L), SO_4^{2-} (medians, 650-810 mg/L) and HCO_3^- (median alkalinity values, 208-290 mg/L as $CaCO_3$; Figs. 18-45 and Table 5). Most product waters from east of the PR had much lower concentrations of Cl^- (range and 5-30 mg/L) and SO_4^{2-} (range, 0.01-28 mg/L) than the surface waters of the mainstem PR (Table 5). However, one product water near Burger Draw had a very high SO_4^{2-} concentration (761 mg/L).

Conductivity of surface waters in the upper and lower PR (not including Clear and Piney Creeks) tended to be high (medians, 2400-2480 μS/cm) but with a wide seasonal range (70-7000 μS/cm; Table 1). Conductivity of CBM product water east of the PR and west of the Little PR was also high, varying from 860 to 3600 μS/cm. K^+ concentrations are similar between surface waters of the PR (medians, 7 mg/L) and nearby product waters (range, 4-18 mg/L).

Hardness of product water from east of the PR (range, 73-264 mg/L as $CaCO_3$) tends to be lower than hardness of the mainstem PR (medians, 510-650 mg/L as $CaCO_3$). This is reflected in lower Ca^{2+} (range, 9-44 mg/L) and Mg^{2+} (range, 5-28 mg/L) concentrations in the product waters and higher Ca^{2+} (medians, 120-150 mg/L) and Mg^{2+} (medians, 49-60 mg/L) in the surface waters.

The pH of local product water (range, pH 7.0-8.0) tended to be slightly lower than median pH values in the PR (pH 8.0-8.1).

Median water temperatures of the upper and lower PR varied from 10 to 12^{o}C, whereas product water temperatures varied from 12 to 26^{o}C. The most important difference in water temperatures is the fact that product water probably will lack distinct seasonal cycles, whereas surface water temperatures varied from 0 to 32°C.

In summary, product water from east of the PR might increase Na^+ and HCO_3^- concentrations in the surface waters of the PR and decrease hardness, Cl^-, and SO_4^{2-} concentrations in the PR. The environmental cue of seasonal cycles in surface water quality (especially temperature) and discharge might be dampened by the influx of product water.

Product Water *Versus* Surface Water: North and South Forks of the Powder River, and Salt Creek

We have no information about CBM product water quality from around the North and South Forks of the PR, and Salt Creek.

Product Water *Versus* Surface Water: Piney Creek, Clear Creek, and Western Portion of Powder River Drainage

We have data from only two CBM product waters near Piney Creek. Both samples tended to be more saline than the surface waters (Figs. 32-45 and Table 5). The product waters had high conductivity (range, 996-1670 μS/cm) and Na^+ concentrations (405 mg/L, n=1), moderate Cl^- concentrations (range, 14-38 mg/L) and low Ca^{2+} (3 mg/L, n=1), Mg^{2+} (3 mg/L, n=1) and SO_4^{2-} (range, 2-8 mg/L) concentrations. The range of pH values was 8.0-9.0. No other water quality parameters were measured. In comparison, Piney Creek had lower median conductivity (640 μS/cm, range 120-1160 μS/cm), Cl^- (2 mg/L) and Na^+ (33 mg/L) concentrations, and higher median Ca^{2+} (62 mg/L), Mg^{2+} (28 mg/L) and SO_4^{2-} (165 mg/L) concentrations. The median pH in Piney Creek was 8.1 (range, 7.3-9.2).

Product Water *Versus* Surface Water: Tongue River and Goose Creek

The limited information on CBM product water (five samples) near the Tongue R suggests that product water conductivity (range, 1630-2180 μS/cm) tends to be much higher than conductivity of the Tongue R (medians, 252-450 μS/cm) and higher than the conductivity (700 μS/cm) measured in Goose Creek, a tributary of the Tongue R (Table 5 and Figs. 46-56).

The high conductivity of the product water near the Tongue R appears to be caused by a high concentration of Na^+ (533 mg/L, n=1) and HCO_3^-. Although the HCO_3^- concentration was not measured directly, the one measurement of alkalinity was 1153 mg/L as $CaCO_3$ at pH 8.6, and would therefore have been mostly due to HCO_3^-. Also, Cl^- and SO_4^{2-} concentrations were low ($\leq$22 mg/l, n=3-4) and would not have contributed much to conductivity. In comparison, the Tongue R and Goose Creek water tended to have low Na^+ concentrations (medians, 1.6-29 mg/L), and Goose Creek had high SO_4^{2-} concentrations (median, 150 mg/L).

Median alkalinity values in the Tongue R and Goose Creek (129 and 235 mg/L as $CaCO_3$, respectively) were lower than in the one product water, whereas median hardness values (130 and 340 mg/L as $CaCO_3$, repectively) were greater than in the one product water (19 mg/L as $CaCO_3$).

Five product water samples from near the Tongue R had pH 7.9-8.6, which encompasses the median pH of surface waters of the Tongue R (pH 8.0-8.1). The only temperature measurement of product water (13°C) was slightly warmer than the median temperatures 5-9°C measured at three USGS stations on the Tongue R and its tributaries. However, as for the PR, the most important difference between water temperatures of the product water and the surface waters is that the product waters will probably lack distinct seasonal cycles, whereas surface waters cycle between temperatures of 0 and 29°C.

In summary, the limited information about product water around the Tongue R suggests that product water might increase the salinity and change the major ion ratios of the Tongue R. This might be especially important in the upper reaches of the Tongue R because such changes in water quality might decrease the habitat quality of these surface waters for salmonid fishes. This is in direct contrast to the potential impact of product water on the PR, in which an influx of CBM product water might decrease the salinity of the surface water.

Product Water *Versus* Surface Water: Little Powder River

We examined data from seven CBM wells in the region of the Little PR (Figs. 57-70 and Table 5). In general, the CBM product water tends to be more "dilute" than the surface waters of the Little PR, except with regard to Na^+ (range, 240-360 mg/L) and alkalinity (range, 810-1520 mg/L as $CaCO_3$). These data suggest that product waters have lower Mg^{2+} (14-46 mg/L, n=5), Ca^{2+} (30-69 mg/L, n=5), K^+ (8.1-15.0 mg/L, n=5) and SO_4^{2-} (0.08-3.00 mg/L, n=5; one outlier of 706 mg/L) concentrations than the surface waters, but have higher HCO_3^- concentrations than the surface waters. Surface water alkalinity was 290 mg/L as $CaCO_3$ (range 190-400 mg/L as $CaCO_3$, n=6). Median ion concentrations in the surface waters were 170 mg Na^+/L, 150 mg Mg^{2+}/L, 280 mg Ca^{2+}/L, 33 mg K^+/L and 1300 mg SO_4^{2-}/L.

Median water temperature in the Little PR was 6.0°C and ranged from 0 to 26°C, whereas the water temperature of six product waters in the region ranged from 13.9 to 26.5°C.

Product Water *Versus* Surface Water: Belle Fourche River

The pH of 26 CBM product waters from around the Belle Fourche R ranged from 6.9 to 7.4, which is lower than the median pH 7.9 measured in the Belle Fourche R (Fig. 79 and Table 5). Alkalinity in the product waters varied from 290 to 1100 mg/L as $CaCO_3$, and tended to be higher than median alkalinity in the Belle Fourche R (242 mg/L as $CaCO_3$; Fig. 71). Although hardness of the product waters was not measured directly, we calculated from the Ca^{2+} and Mg^{2+} concentrations that hardness ranged from approximately 21 to 225 mg/L as $CaCO_3$ (Fig. 77). Because the median hardness of the Belle Fourche R was 1500 mg/L as $CaCO_3$, product waters appear to have lower hardness than surface waters in the area.

Belle Fourche R waters have high median conductivity (3800 μS/cm); and even minimum conductivity measured in the river is high (minimum, 1100 μS/cm; maximum 8000 μS/cm; Table 1). High Na^+ (median, 385 mg/L), SO_4^{2-} (median, 2000 mg/L), Ca^{2+} (median, 290 mg/L), and Mg^{2+} (median, 160 mg/L) concentrations all contribute to the high conductivity. In the product water, Na^+ (range, 110-390 mg/L) and Cl^- (range, 5-64 mg/L) concentrations were higher, but SO_4^{2-} (range, 0.01-12 mg/L), Ca^{2+} (range, 6-56 mg/L) and Mg^{2+} (range, 2-25 mg/L) concentrations were much lower than the Belle Fourche R (Table 5 and Figs. 73, 74, 78, 81 and 82). Consequently, the conductivity of product waters (range, 470-1640 μS/cm) was lower than in the Belle Fourche R. Median water temperature of the Belle Fourche R was 13.5°C (range, 0-29°C), whereas product waters tended to be warmer (range, 14-29°C; Fig. 83).

In summary, the CBM product waters from around the Belle Fourche R tend to be more "dilute" than surface waters of the Belle Fourche R, except with regard to alkalinity (and, consequently HCO_3^-), Na^+ and Cl^- concentrations.

Product Water *Versus* Surface Water Quality: Summary and Recommendations

- More data from CBM product water sampling is needed to adequately assess product water quality, especially from around Clear Creek, Piney Creek (western portion of the PR drainage), the southern portion of the PR drainage (North and South Forks of the PR , and Salt Creek), and the Tongue R.

- Surface water quality and CBM product water quality vary considerably across the PRB. Therefore, CBM product water quality will have different impacts on the different surface waters of the PRB. For example, product waters will tend to "dilute" the waters of the Belle Fourche R, whereas product waters will tend to "salinate" the waters of the Tongue R. We recommend that the tendency for CBM product waters to "dilute" some surface waters be considered just as potentially important to resident biota as is the tendency for CBM product waters to "salinate" other surface waters.
- Because the Tongue River (to at least the Montana border), Piney Creek, Clear Creek (to several km downstream from Piney Creek), Crazy Woman Creek (to approximately I-25), the North Fork of the Powder River, and the Middle Fork of the Powder River (to approximately I-25) provide relatively high-quality, low-salinity habitat for salmonid fishes (see Surface Waters: Temperature section), major increases in salinity and changes in ion ratios in those surface waters due to discharge of CBM product water might have significant impacts on recreational fisheries.

Biological Methods to Examine the Impacts of Coalbed Methane Product Waters on Aquatic Organisms of the Powder River Basin

Standard testing organisms used to monitor freshwater quality in the USA include the invertebrates *Daphnia magna, D. pulex* and *Ceriodaphnia dubia*, and the fish species fathead minnow (*Pimephales promelas*), rainbow trout (*Oncorhynchus mykiss*) and brook trout (*Salvelinus fontinalis*; USEPA 1993). These species were chosen by the USEPA because they "are easily cultured in the laboratory, are sensitive to a variety of pollutants, and are generally available throughout the year from commercial sources." *D. magna* and *C. dubia* are widely distributed invertebrates (USEPA 1993) and are probably resident in some surface waters of the PRB; and fathead minnows are resident in some tributaries of the PR (Hubert 1993). Because toxicity testing protocols have already been developed for these three species and they are either definitely or probably resident in some surface waters of the PRB, they are appropriate species for conducting initial toxicity testing. However, there are two important factors that should guide future toxicity testing.

First, the waters of the PR, the Little PR and Belle Fourche R tend to be saline; and at times, and in some locations, either median alkalinity, hardness, Na^+, SO_4^{2-}, or Cl^- concentrations exceed toxic concentrations (24-h, 48-h, 96-h or chronic LC50s) for one or all of the test organisms (Table 6). Therefore, other species might be more appropriate for toxicity testing in some surface waters of the PRB. In addition, receiving waters should be tested for their influence on toxicity, separate from the effects of product water.

Secondly, because 32 species of fish (Hubert 1993) and at least 19 species of aquatic invertebrates (Elser et al. 1977) are present in the PRB, it might be appropriate to either test a wider range of species or use *in situ* toxicity testing methods (discussed below). However, the difficulties involved in maintaining and rearing non-standard species in the laboratory might preclude such testing with some species. We have not found any data about the toxicity of major ions to fish species that are native to the PRB.

Even with the limited data we have surveyed, alkalinity and Na^+, SO_4^{2-}, and Cl^- concentrations in some CBM product waters exceed the acutely toxic concentrations (24-h, 48-h or 96-h LC50s) for *C. dubia*, *D. magna*, and fathead minnows, indicating that toxicity to aquatic biota could occur if relatively large volumes of CBM product water are released to some surface waters of the PRB (Table 6).

Due to the complex and widely varying composition of product waters, a simple comparison of concentrations of single components of the product waters to LC50s could either overestimate or underestimate toxicity to the test species. Therefore, whole-effluent toxicity testing is essential to understand the potential impacts of CBM product waters on aquatic organisms.

Another possibility for assessing the effect of CBM product waters on aquatic communities in the surface waters of the PRB is the *in situ* bioassessment method proposed by O'Neil and Harris (1992). They used instream monitoring to assess the effect of product water effluent on the structure of benthic macroinvertebrate communities downstream of permitted discharge points. The technique was developed to be practical but statistically rigorous. Multi-plate samplers were placed in reference waterways (usually above the discharge point) and left for 6 weeks in order to allow colonization of the plates by benthic invertebrate communities. Next, half the plates were moved to the testing site below the discharge point and exposed to the receiving waters for 14 d. After 14 d, the species compositions of the invertebrate communities on the two sets of plates were statistically compared. In concept, this technique could be used in the PRB.

Biological Methods: Recommendations

- We recommend that toxicity testing be conducted on receiving waters as well as whole effluents from CBM wells.
- In addition to standard laboratory testing species, we recommend that toxicity testing be conducted using species resident in the surface waters of the PRB, if possible.
- We recommend that instream bioassessment be conducted to directly assess the potential impacts of CBM product water on local aquatic communities.

Ecology

Some important effects of CBM product water on the surface waters of the PRB can not be analyzed by traditional toxicity testing approaches. The composition of aquatic communities is determined by many factors, including flow regime and temporal variability of the water quality. For example, the PR is characterized by its variable nature. "The Powder River is a turbid, saline, meandering stream with a highly braided, unstable sand bottom. Discharge is highly erratic, and the river is intermittent during dry years upstream from the mouth of Clear Creek, 16 km upstream from the Montana-Wyoming state line" (Hubert 1993). In other words, the PR is not a "blue ribbon trout fishery"; instead it is an unique remnant of the type of waterways that were once common in the Great Plains region of North America. The PR is now ecologically valuable because it supports a relatively intact assemblage of native species and "has been relatively unaffected by water development, channelization, introduction of exotic species, [and] exploitation of fish stocks" (Hubert 1993). Ironically, addition of constant flows of relatively low-salinity CBM product waters could alter the nature of the PR in a manner that will favor the introduction of exotic species at the expense of native species (Cross et al. 1985, Sanders et al. 1993, Rabeni 1996).

Ecology: Recommendations

- We recommend that the potential impacts of CBM product water on the aquatic communities inhabiting the surface waters of the PRB be assessed with respect to how much they will change local water quality characteristics from current conditions and, thus, potentially alter the composition of the local aquatic communities.
- We recommend that management goals for the future of the surface waterways of the PRB be

established and/or refined to guide decisions about how much change in current conditions is acceptable. For example, if the native fish communities of the PR are to be maintained, their habitat requirements will have to be considered relative to the potential impacts of CBM product waters that might tend to favor exotic species.

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Table 1. Median values (minimum and maximum in parentheses) of water quality parameters from surface water quality data collected by the U.S. Geological Survey (USGS) from 1951 to 1999 in several drainages in the Powder River Basin of Wyoming. Locations, sampling dates, and number of days sampled are listed in Table 2.

Parameter	Tongue River Upstream	Tongue River Downstream	Goose Creek	Piney Creek	Clear Creek Upstream	Clear Creek Downstream	South Fork Powder River	Salt Creek	Crazy Woman Creek	Powder River Upstream	Powder River Downstream	Little Powder River	Belle Fourche River
USGS site #	6298000	6299980	6305500	6323500	6320200	6324000	6313000	6313400	6316400	6313500	6317000	6324890	6425720
Temperature (^oC)	5 (0.0-20.6)	8.8 (0.0-23.0)	9.0 (0.0-29.0)	9.8 (0.0-26.0)	8.8 (0.0-25.0)	10.0 (0.0-29.0)	10.0 (0.0-32.0)	9.8 (0.0-31.0)	12.5 (0.0-28.0)	10.0 (0.0-29.0)	11.5 (0.0-32.0)	6.0 (0.0-25.5)	13.5 (0.0-28.5)
pH (standard units)	8.1 (6.8-8.6)	8.0 (6.9-8.9)	8.1 (6.7-8.9)	8.1 (7.3-9.2)	8.2 (7.5-8.9)	8.0 (7.2-8.8)	7.9 (6.8-8.5)	8.1 (7.1-8.9)	8.0 (7.1-8.5)	8.1 (6.4-8.5)	8.0 (6.6-9.0)	7.9 (7.4-8.5)	7.9 (7.2-8.5)
Conductivity (μS/cm at 25^{o}C)	252 (50-360)	450 (170-660)	700 (63-1210)	640 (120-1160)	825 (130-1300)	1145 (230-2360)	3295 (301-6200)	6770 (1700-8870)	1620 (348-4170)	2400 (655-7000)	2480 (70-6500)	2610 (1300-5920)	3800 (1100-8000)
Dissolved oxygen (mg/L)	10.6 (7.6-13.2)	10.4 (7.9-13.6)	10.6 (5.6-15.4)	10.2 (6.6-12.9)	10.6 (8.0-17.5)	10.0 (7.1-13.0)	10.2 (6.2-12.9)	8.3 (0.7-15.0)	9.3 (5.6-14.0)	9.0 (4.5-15.3)	8.8 (2.9-12.8)	8.9 (3.4-16.8)	9.9 (6.3-13.8)
Alkalinity (mg/L as $CaCO_3$)	129 (41-172)	191 (70-244)	235 (41-317)	160 (35-280)	160 (20-240)	199 (50-462)	149 (73-410)	618 (150-1160)	200 (61-3710)	290 (138-640)	208 (102-509)	290 (190-400)	242 (90-400)
Hardness (mg/L as $CaCO_3$)	130 (58-180)	230 (77-340)	340 (60-543)	260 (22-480)	355 (47-590)	480 (71-1030)	1100 (403-1800)	400 (190-970)	700 (180-2200)	510 (240-1400)	650 (270-2800)	1300 (530-3300)	1500 (380-3500)
Na^+ (mg/L)	1.6 (0.0-240)	15.0 (2.4-46)	29.0 (4.2-63)	33.0 (4.9-74)	44.0 (5.7-80)	71.0 (9.6-200)	420 (164-970)	1400 (290-2000)	120 (12-380)	350 (57-1400)	350 (66.0-1500)	170 (75.0-600)	385 (100-1200)
K^+ (mg/L)	0.7 (0.0-6.7)	1.8 (0.3-7.4)	2.9 (0.0-39.0)	4.4 (1.1-16.0)	2.8 (0.5-12.0)	4.4 (0.6-46.0)	9.3 (0.8-24.0)	17.0 (1.6-65.0)	4.2 (2.0-16.0)	7.0 (1.4-23.0)	6.7 (0.6-59.0)	33.0 (3.0-56.0)	14.5 (6.4-45.0)
Ca^{2+} (mg/L)	34 (12-56)	51 (21-67)	65 (12-150)	62 (12-100)	84 (12-130)	110 (23-1470)	300 (32-550)	80 (22-290)	150 (42-582)	120 (31-290)	150 (50-408)	280 (96-420)	290.0 (95-530)
Mg^{2+} (mg/L)	11.0 (0.8-29.0)	24.0 (6.0-48.0)	43.0 (4.3-80.0)	28.0 (3.9-56.0)	35.5 (4.2-64.0)	54.0 (7.6-118)	80.0 (14.0-170)	51.0 (7.8-297)	77.5 (6.8-260.0)	49.0 (14.0-160)	60.0 (6.7-228)	150.0 (70.0-600)	160 (35.0-530)
Cl^- (mg/L)	1.1 (0.0-24.0)	2.0 (0.7-17.0)	5.4 (0.0-23.0)	2.4 (1.0-6.2)	4.2 (0.1-7.6)	4.5 (0.0-48.0)	110.0 (16.0-643)	1200.0 (63.0-1980)	9.4 (1.7-120)	220.0 (0.7-1600)	210.0 (3.7-1300.0)	10.0 (5.1-26.0)	19.0 (4.1-55.0)
SO_4^{2-} (mg/L)	5 (0-19)	68 (11-240)	150 (14-394)	165 (20-370)	280 (31-490)	439 (60-1130)	1510 (124-3200)	1100 (460-4349)	700 (77-2700)	650 (140-2300)	810 (203-2580)	1300 (560-3900)	2000.0 (510-5400)
Turbidity (JCU)	1 (0-20)	4 (1-100)	8 (1-90)	2 (0-33)	3 (1-15)	9 (1-500)	65 (1-550)	200 (20-2600)	55 (10-100)	145 (90-200)	475 (20-8000)	2 (1-25)	8 (2-25)
Discharge (ft^3/s)	77 (34-2310)	111 (43-2200)	94 (6.6-5540)	52 (10-1090)	53 (7.6-1240)	96 (1.9-3540)	12 (0.0-1400)	31 (3.6-2360)	26 (0.03-1670)	155 (6.3-10,680)	171 (2.0-17,800)	0.6 (0.0-402)	0.1 (0.0-1400)

Table 2. U.S. Geological Survey (USGS) site number, decimal degree location, dates of collection, and number of sampling days for the USGS surface water quality dataset (Table 1).

Site	USGS site #	Decimal degree location (N, W)	Dates of collection	Number of sampling days
Tongue River Upstream	6298000	44.83, 107.30	10/10/66-9/24/81, 1/14/99-8/31/99	192
Tongue River Downstream	6299980	44.90, 107.02	4/3/74-9/20/83	79
Goose Creek	6305500	44.83, 106.99	1/22/68-7/29/99	268
South Fork Powder River	6313000	43.62, 106.57	4/10/51-9/10/51, 6/12/68-10/21/92	245
Salt Creek	6313400	43.62, 106.37	10/9/67-7/28/99	275
Powder River Upstream	6313500	43.68, 106.28	10/11/66-7/31/68, 11/1/77-7/28/99	233
Crazy Woman Creek	6316400	44.48, 106.17	11/14/66-7/21/99	190
Powder River Downstream	6317000	44.64, 106.12	10/2/67-7/21/99	377
Clear Creek Upstream	6320200	44.35, 106.65	11/11/75-9/9/91	74
Piney Creek	6323500	44.55, 106.53	7/3/75-9/14/92	75
Clear Creek Downstream	6324000	44.87, 106.07	10/10/66-8/7/89	235
Little Powder River	6324890	44.48, 105.47	5/5/78-8/12/83	46
Belle Fourche River	6425720	43.98, 105.38	11/16/75-9/27/80	36

Table 3. Median molar concentrations of anions (HCO_3^-, CO_3^{2-}, Cl^-, SO_4^{2-}, OH^-) and cations (Ca^{2+}, Mg^{2+}, K^+, Na^+, H^+) at U.S. Geological Survey (USGS) sites on surface waters of the Powder River Basin in Wyoming. The concentrations in mg/L from which these molar concentrations were calculated are listed in Table 1.

	USGS	Concentrations of cations (mM)						Concentrations of anions (mM)					
Location	site #	Ca^{2+}	Mg^{2+}	K^+	Na^+	H^+	Sum	HCO_3^-	CO_3^{2-}	Cl^-	SO_4^{2-}	OH^-	Sum
Tongue River Upstream	6298000	0.85	0.45	0.02	0.07	<0.01	1.39	2.55	0.02	0.03	0.05	<0.01	2.65
Tongue River Downstream	6299980	1.27	0.99	0.05	0.65	<0.01	2.96	3.78	0.02	0.06	0.71	<0.01	4.57
Goose Creek	6305500	1.62	1.77	0.07	1.26	<0.01	4.73	4.65	0.03	0.15	1.56	<0.01	6.39
South Fork Powder River	6313000	7.49	3.29	0.24	18.29	<0.01	29.31	2.96	0.01	3.10	15.72	<0.01	21.79
Salt Creek	6313400	2.00	2.10	0.43	60.90	<0.01	65.43	12.22	0.07	33.85	11.45	<0.01	57.59
Powder River Upstream	6313500	2.99	2.02	0.18	15.22	<0.01	20.41	5.73	0.03	6.21	6.77	<0.01	18.74
Crazy Woman Creek	6316400	3.74	3.19	0.11	5.22	<0.01	12.26	3.96	0.02	0.27	7.29	<0.01	11.53
Powder River Downstream	6317000	3.74	2.47	0.17	15.22	<0.01	21.61	4.12	0.02	5.92	8.43	<0.01	18.50
Clear Creek Upstream	6320200	2.10	1.46	0.07	1.91	<0.01	5.54	3.15	0.02	0.12	2.91	<0.01	6.21
Piney Creek	6323500	1.55	1.15	0.11	1.44	<0.01	4.25	3.16	0.02	0.07	1.72	<0.01	4.97
Clear Creek Downstream	6324000	2.74	2.22	0.11	3.09	<0.01	8.17	3.94	0.02	0.13	4.57	<0.01	8.66
Little Powder River	6324890	6.99	6.17	0.84	7.39	<0.01	21.40	5.76	0.02	0.28	13.53	<0.01	19.60
Belle Fourche River	6425720	7.24	6.58	0.37	16.75	<0.01	30.94	4.80	0.02	0.54	20.82	<0.01	26.18

Table 4. Percentages of anions (HCO_3^-, CO_3^{2-}, Cl^-, SO_4^{2-}, OH^-) and cations (Ca^{2+}, Mg^{2+}, K^+, Na^+, H^+) at U.S. Geological Survey (USGS) sites on surface waters of the Powder River Basin in Wyoming. These percentages are based on the median molar concentrations listed in Table 3.

Location	USGS site #	Percentages of cations						Percentages of anions					
		Ca^{2+}	Mg^{2+}	K^+	Na^+	H^+	Sum	HCO_3^-	CO_3^{2-}	Cl^-	SO_4^{2-}	OH^-	Sum
Tongue River Upstream	6298000	61	33	1	5	<1	100	96	1	1	2	<1	100
Tongue River Downstream	6299980	43	33	2	22	<1	100	83	<1	1	15	<1	100
Goose Creek	6305500	34	37	2	27	<1	100	73	<1	2	24	<1	100
South Fork Powder River	6313000	26	11	1	62	<1	100	14	<1	14	72	<1	100
Salt Creek	6313400	3	3	1	93	<1	100	21	<1	59	20	<1	100
Powder River Upstream	6313500	15	10	1	75	<1	100	31	<1	33	36	<1	100
Crazy Woman Creek	6316400	31	26	1	43	<1	100	34	<1	2	63	<1	100
Powder River Downstream	6317000	17	11	1	70	<1	100	22	<1	32	46	<1	100
Clear Creek Upstream	6320200	38	26	1	35	<1	100	51	<1	2	47	<1	100
Piney Creek	6323500	36	27	3	34	<1	100	64	<1	1	35	<1	100
Clear Creek Downstream	6324000	34	27	1	38	<1	100	46	<1	1	53	<1	100
Little Powder River	6324890	33	29	4	35	<1	100	29	<1	1	69	<1	100
Belle Fourche River	6425720	23	21	1	54	<1	100	18	<1	2	80	<1	100

Table 5. Ranges of water quality in surface waters of several drainages in the Powder River Basin of Wyoming *versus* quality of product waters from coalbed methane wells located in the same drainage. Surface water quality parameters are medians of U.S. Geological Survey data (Table 1). Product water data are the range of values from wells located in the same drainage (sample sizes in parentheses). --- = not analyzed.

	Eastern Portion of Powder River Drainage		Western Portion of Powder River Drainage		Little Powder River Drainage		Belle Fourche River Drainage		Tongue River Drainage		
Parameter	Surface Powder River	Product East Powder River	Surface Piney Creek	Product West Powder River	Surface Little Powder River	Product Little Powder River	Surface Belle Fourche River	Product Belle Fourche River	Surface Tongue River	Surface Goose Creek	Product Tongue River
Temperature (°C)	10-12	12-26 (12)	10	---	6	14-27 (6)	14	14-29 (26)	5-9	9.0	13 (1)
pH (standard units)	8.0-8.1	7.0-8.0 (26), 9.0 (1)	8.1	8.0-9.0 (2)	7.9	6.8-7.9 (7)	7.9	6.9-7.4 (26)	8.0-8.1	8.1	7.9-8.6 (5)
Conductivity (μS/cm)	2400-2480	860-3600 (27)	640	996-1670 (2)	2610	1070-1660 (6), 5300 (1)	3800	470-1640 (26)	252-450	700	1630-2180 (5)
Alkalinity (mg/L as $CaCO_3$)	208-290	580-2440 (14)	160	---	290	810-1520 (6)	242	290-1100 (26)	129-191	235	1153 (1)
Hardness (mg/L as $CaCO_3$)	510-650	73-264 (15)	260	---	1300	192 (1)	1500	100 (1)	130-230	340	19 (1)
Ca^{2+} (mg/L)	120-150	9-44 (19)	62	3 (1)	280	30-69 (5)	290	6-56 (25)	34-51	65	9 (1)
K^{+} (mg/L)	7	4-18 (11)	4	---	33	8-15 (5)	15	4-14 (25)	1-2	3	---
Mg^{2+} (mg/L)	49-60	5-28 (19)	28	3 (1)	150	14-46 (5)	160	2-25 (25)	11-24	43	2 (1)
Na^{+} (mg/L)	350	409-994 (24)	33	405 (1)	170	240-360 (5)	385	110-390 (25)	1.6-15	29	533 (1)
Cl^{-} (mg/L)	210-220	5-30 (25), 170 (1)	2	14-38 (2)	10	9-12 (5), 1260 (1)	19	5-64 (25)	1-2	5	17-22 (4)
SO_4^{2-} (mg/L)	650-810	0.01-28 (24), 761(1)	165	2-8 (2)	1300	0.08-3.0 (5), 706 (1)	2000	0.01-12.0 (25)	5-68	150	2-19 (4)

Table 6. Range of LC50s (median lethal concentrations) for *Ceriodaphnia dubia, Daphnia magna* and fathead minnows (*Pimephales promelas*), exposed to different compounds or ions; and concentrations of those compounds or ions in surface waters and coalbed methane (CBM) product waters from the Powder River Basin, Wyoming. x = concentration of the compound or ion in either surface water (S) or CBM product water (P) exceeded the LC50 of the test organism (i.e., toxicity might occur in full-strength water), 0 = LC50 not exceeded, --- = no data available. Data for surface water quality are the median values in the U.S. Geological Survey dataset (Table 1). Data for CBM product water quality are the range of values reported in datasets A to D in this report. See text for additional details about those datasets.

			Fathead minnow			*Ceriodaphnia dubia*			*Daphnia magna*			
Parameter or ion	Units	Exposure duration (h)	LC50 (mg/L)	S	P	LC50 (mg/L)	S	P	LC50 (mg/L)	S	P	Source of LC50 data
Alkalinity	mg/L as $CaCO_3$	Chronic	---	---	---	183-306	x	x	592-1006	0	x	Cowgill and Milazzo (1991a)
Hardness	mg/L as $CaCO_3$	Chronic	---	---	---	1031	x	0	1516	x	0	Cowgill and Milazzo (1990)
Na^+	mg/L	24	1328-3255	x	0	389-1329	x	x	652-2508	x	x	Mount et al. (1997)
	mg/L	48	685-2577	x	x	279-997	x	x	449-1875	x	x	Mount et al. (1997)
	mg/L	96	233-2577	x	x	---	---	---	---	---	---	Mount et al. (1997)
K^+	mg/L	24	367-498	0	0	246-345	0	0	262-388	0	0	Mount et al. (1997)
	mg/L	48	320-477	0	0	246-330	0	0	254-346	0	0	Mount et al. (1997)
	mg/L	96	199-461	0	0	---	---	---	---	---	---	Mount et al. (1997)
Ca^{2+}	mg/L	24	580-2404	0	0	571-816	0	0	580-1173	0	0	Mount et al. (1997)
	mg/L	48	580-2368	0	0	562-661	0	0	580-1000	0	0	Mount et al. (1997)
	mg/L	96	580-1671	0	0	---	---	---	---	---	---	Mount et al. (1997)
Mg^{2+}	mg/L	24	898-934	0	0	324-357	0	0	398-476	0	0	Mount et al. (1997)
	mg/L	48	708-724	0	0	224-357	0	0	339-367	0	0	Mount et al. (1997)
	mg/L	96	541-569	0	0	---	---	---	---	---	---	Mount et al. (1997)
Cl^-	mg/L	24	452-5025	x	x	300-2051	x	x	352-3872	x	x	Mount et al. (1997)
	mg/L	48	433-4192	x	x	300-1189	x	x	314-2895	x	x	Mount et al. (1997)
	mg/L	96	419-3878	x	x	---	---	---	---	---	---	Mount et al. (1997)
SO_4^{2-}	mg/L	24	546-5464	x	x	425-2428	x	x	469-4254	x	x	Mount et al. (1997)
	mg/L	48	474-5383	x	x	375-2082	x	x	397-3097	x	x	Mount et al. (1997)
	mg/L	96	375-5383	x	x	---	---	---	---	---	---	Mount et al. (1997)
HCO_3^-	mg/L	24	573-3522	---	---	384-1031	---	---	408-1728	---	---	Mount et al. (1997)
	mg/L	48	500-1815	---	---	384-741	---	---	396-1191	---	---	Mount et al. (1997)
	mg/L	96	311-617	---	---	---	---	---	---	---	---	Mount et al. (1997)

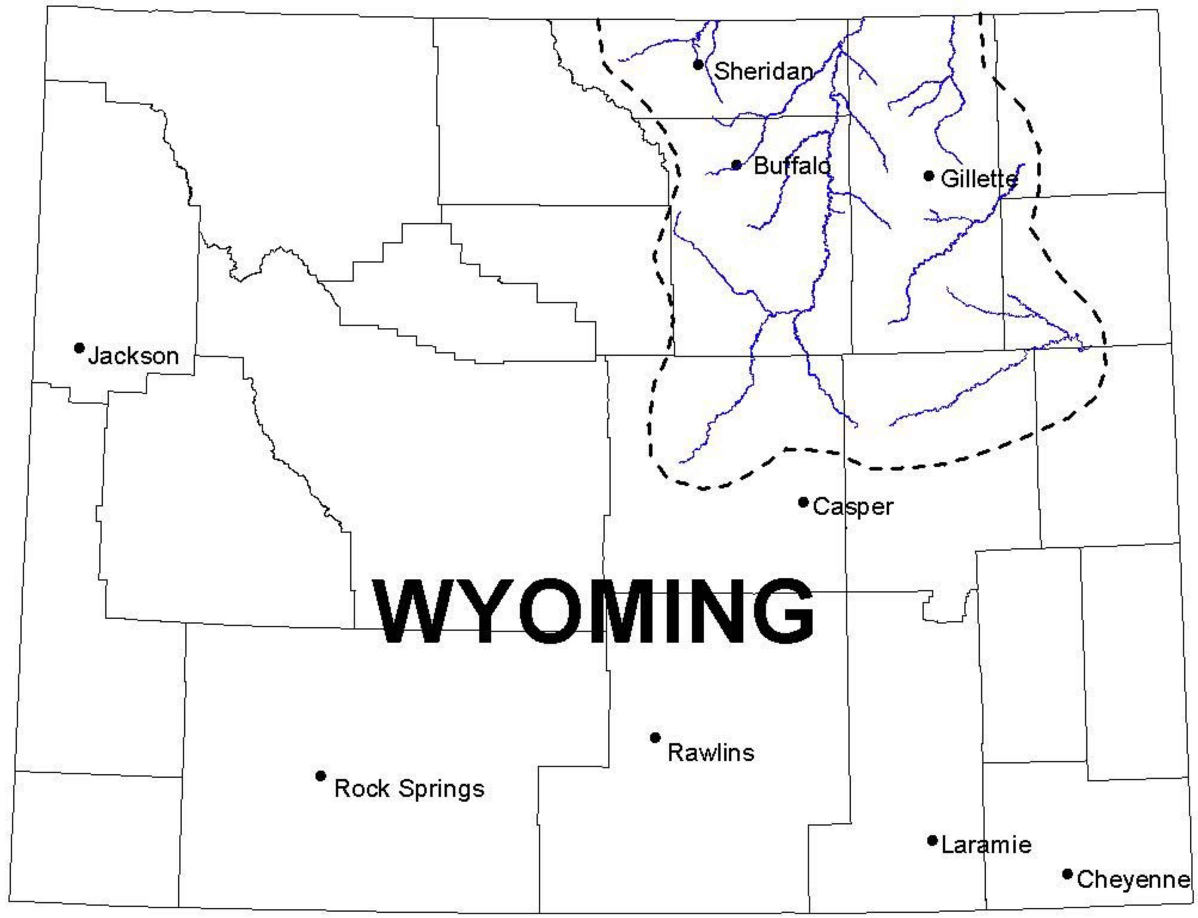

Figure 1. Location of the Powder River Basin (inside dashed boundary) in Wyoming.

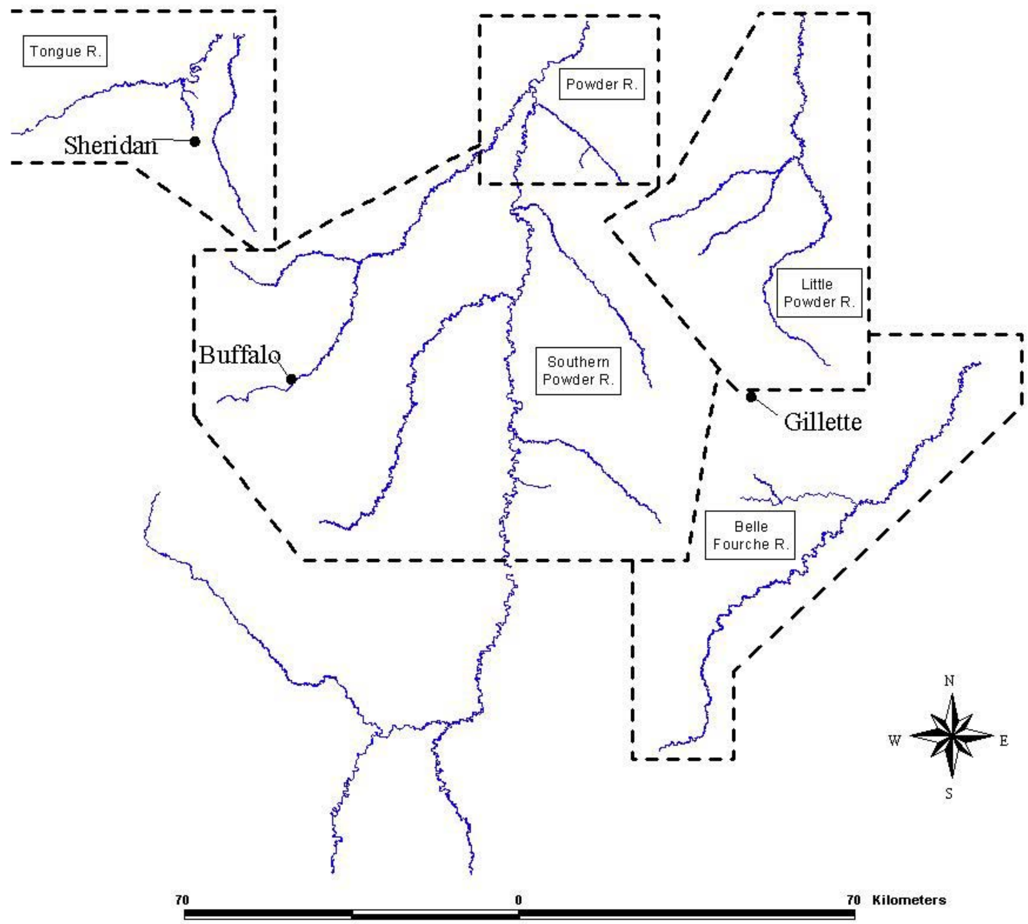

Figure 2. Major cities in the Powder River Basin of Wyoming, and boundaries of the sub-basin maps (Powder R. - Figs. 18-31; Southern Powder R. - Figs. 32-45; Tongue R. - Figs. 46-56; Little Powder R. - Figs. 57-70; and Belle Fourche R. - Figs. 71-84).

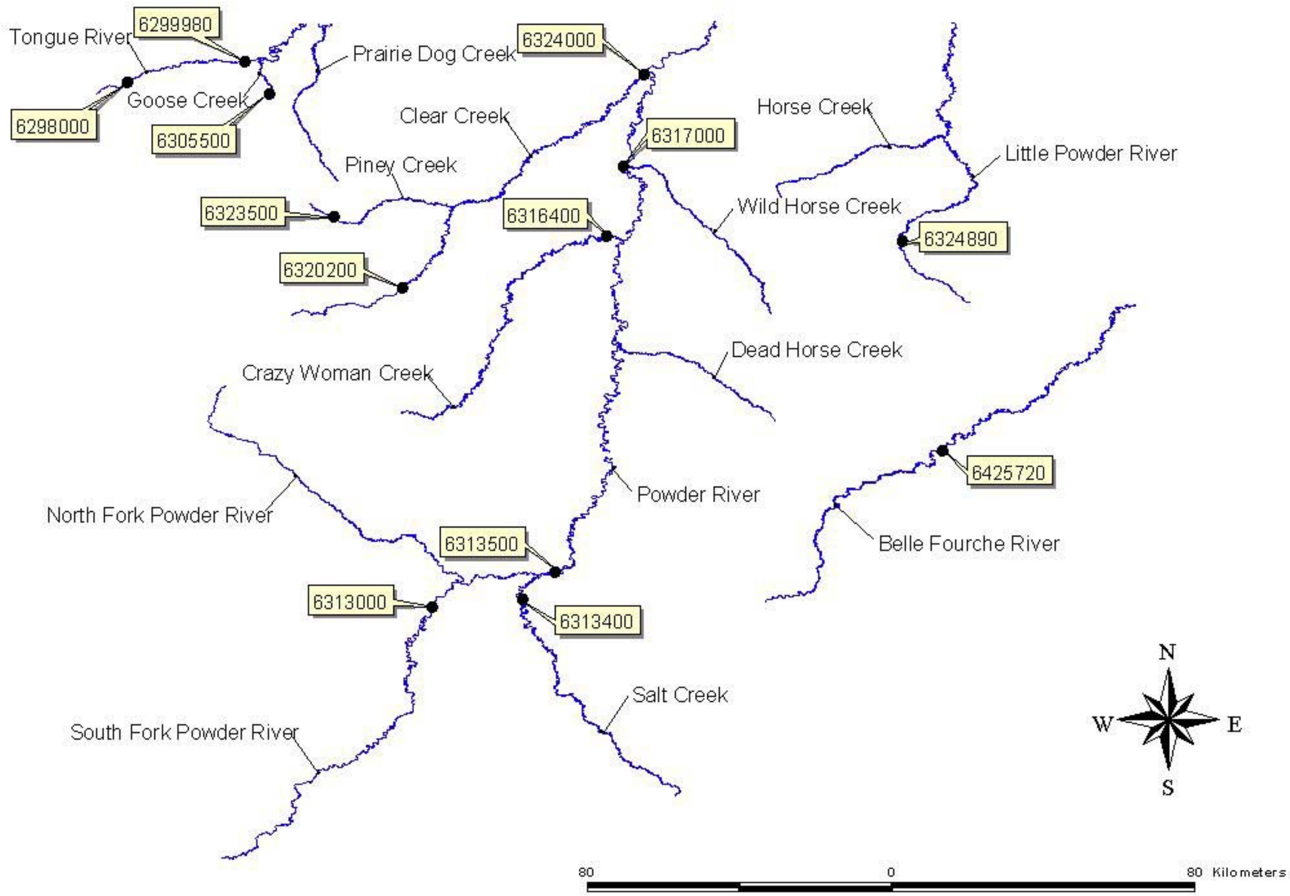

Figure 3. Major waterways and their tributaries in the Powder River Basin of Wyoming. USGS gauging stations used to measure surface water quality are shown with their numerical identifiers (see also Table 2).

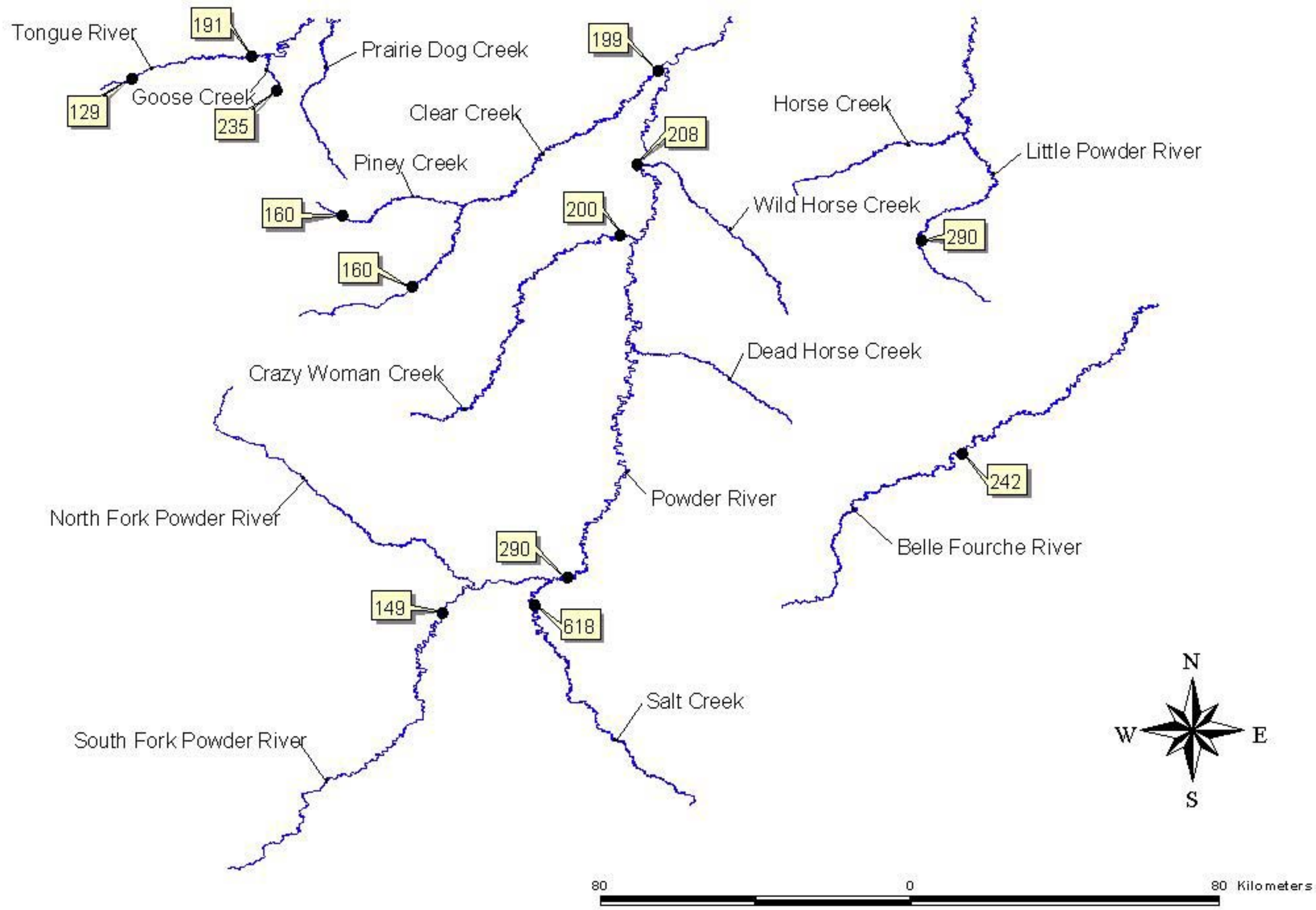

Figure 4. Median alkalinity values (mg/L as $CaCO_3$) in surface waters of the Powder River Basin of Wyoming, measured at USGS gauging stations from 1951 until 1999. Refer to Tables 1 and 2 for details about the locations of the gauging stations.

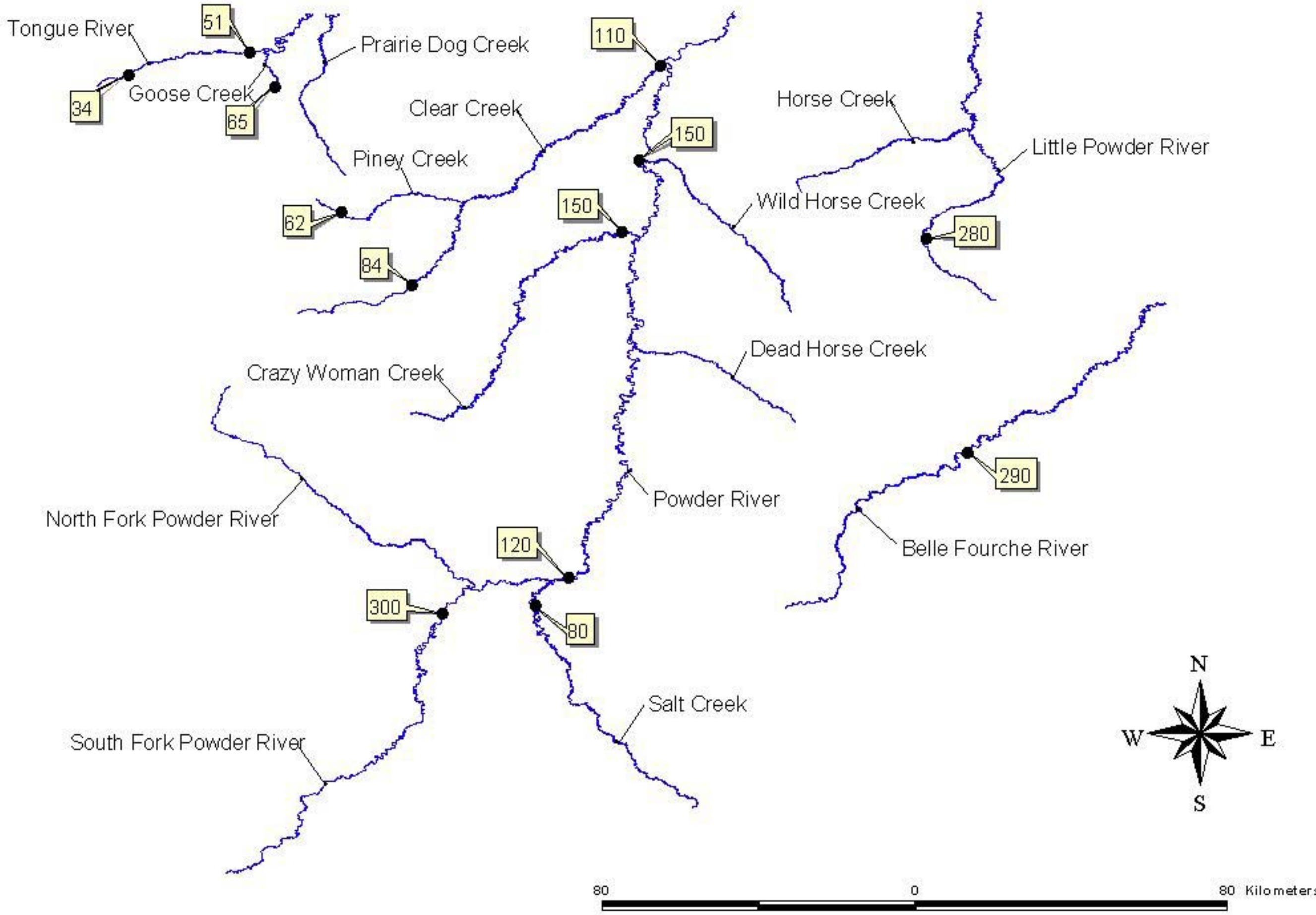

Figure 5. Median calcium concentrations (mg/L) in surface waters of the Powder River Basin of Wyoming, measured at USGS gauging stations from 1951 until 1999. Refer to Tables 1 and 2 for details about the locations of the gauging stations.

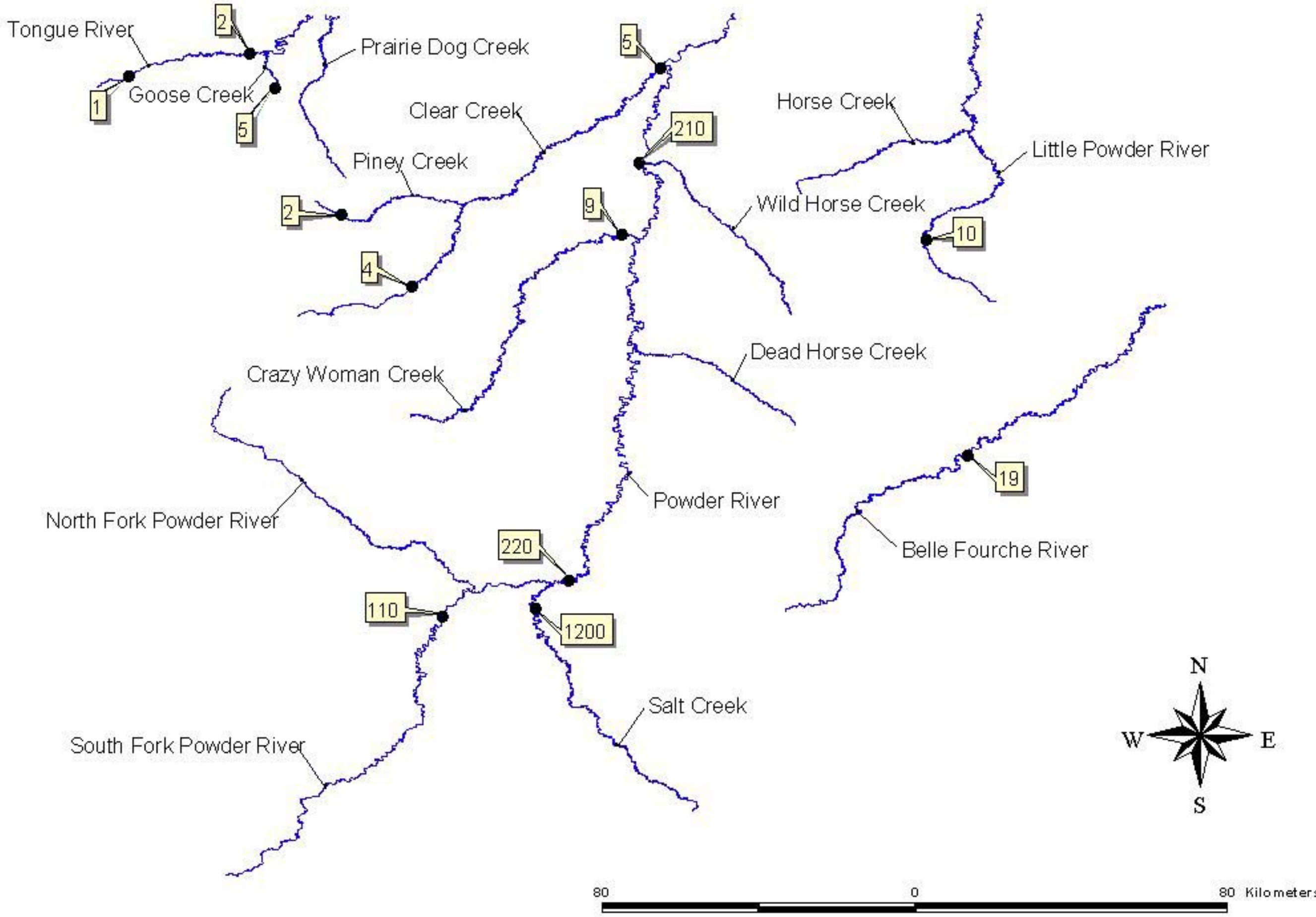

Figure 6. Median chloride concentrations (mg/L) in surface waters of the Powder River Basin of Wyoming, measured at USGS gauging stations from 1951 until 1999. Refer to Tables 1 and 2 for details about the locations of the gauging stations.

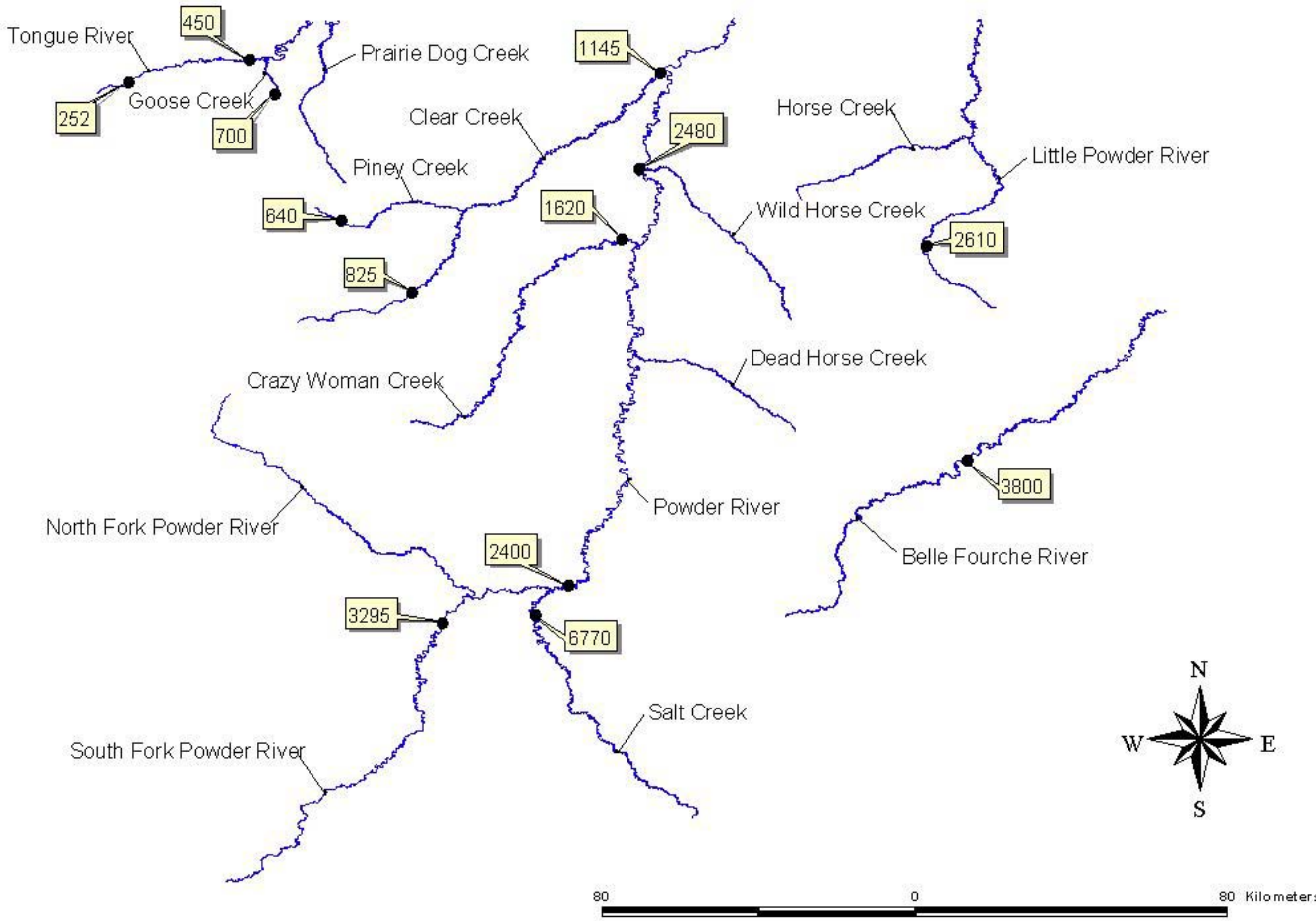

Figure 7. Median conductivity values (μS/cm) in surface waters of the Powder River Basin of Wyoming, measured at USGS gauging stations from 1951 until 1999. Refer to Tables 1 and 2 for details about the locations of the gauging stations.

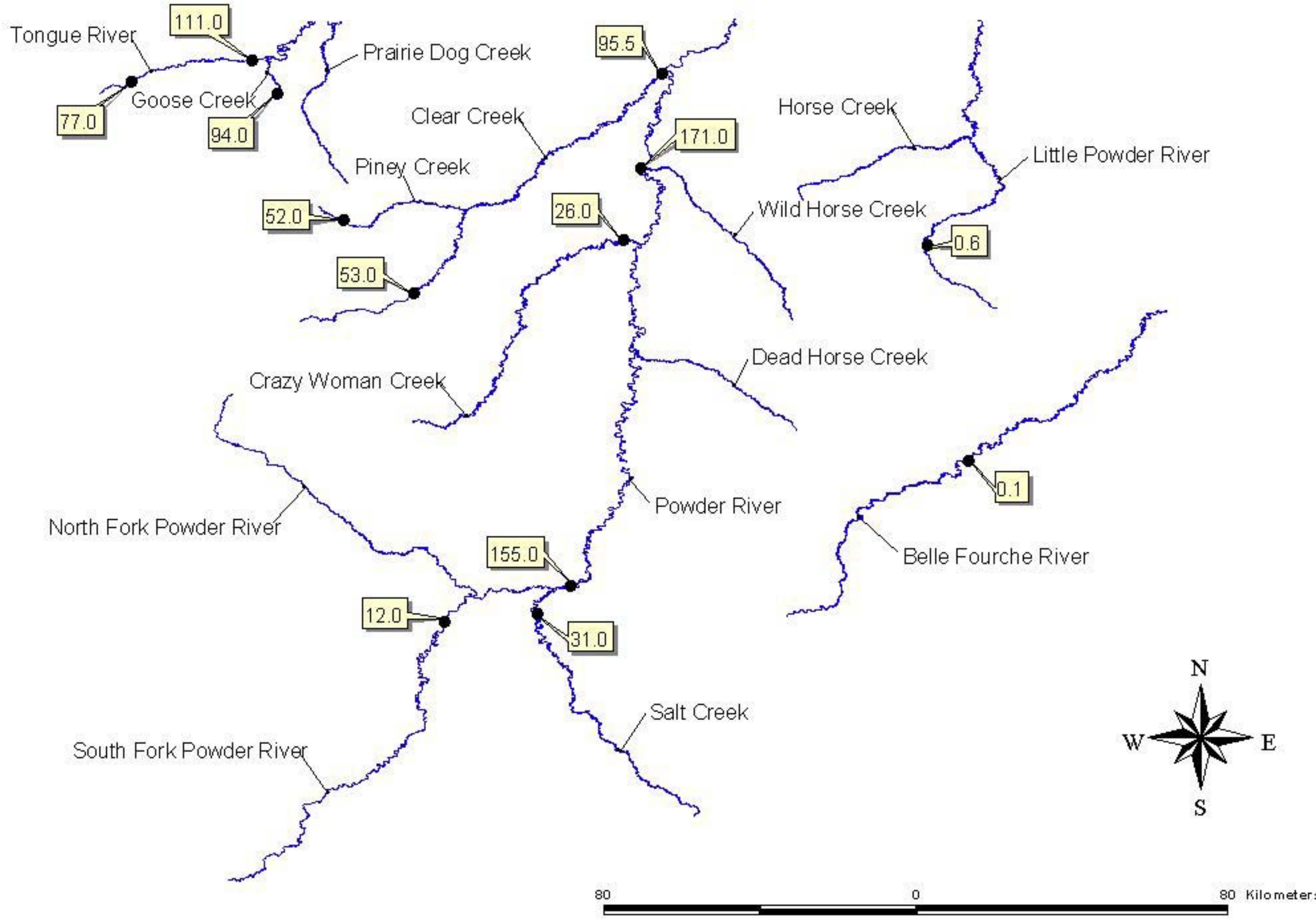

Figure 8. Median discharge (ft^3/s) of surface waters of the Powder River Basin of Wyoming, measured at USGS gauging stations from 1951 until 1999. Refer to Tables 1 and 2 for details about the locations of the gauging stations.

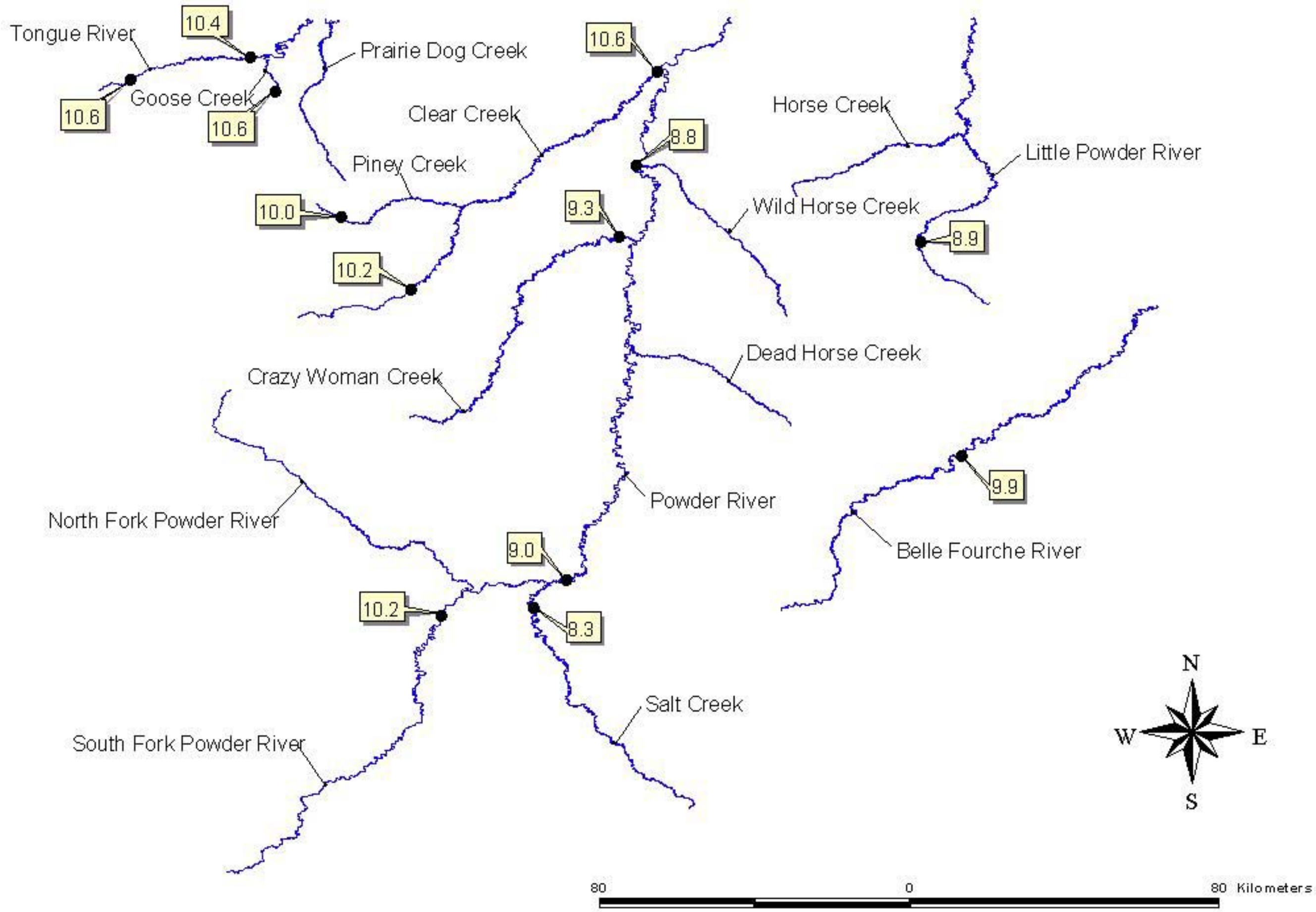

Figure 9. Median dissolved oxygen concentrations (mg/L) in surface waters of the Powder River Basin of Wyoming, measured at USGS gauging stations from 1951 until 1999. Refer to Tables 1 and 2 for details about the locations of the gauging stations.

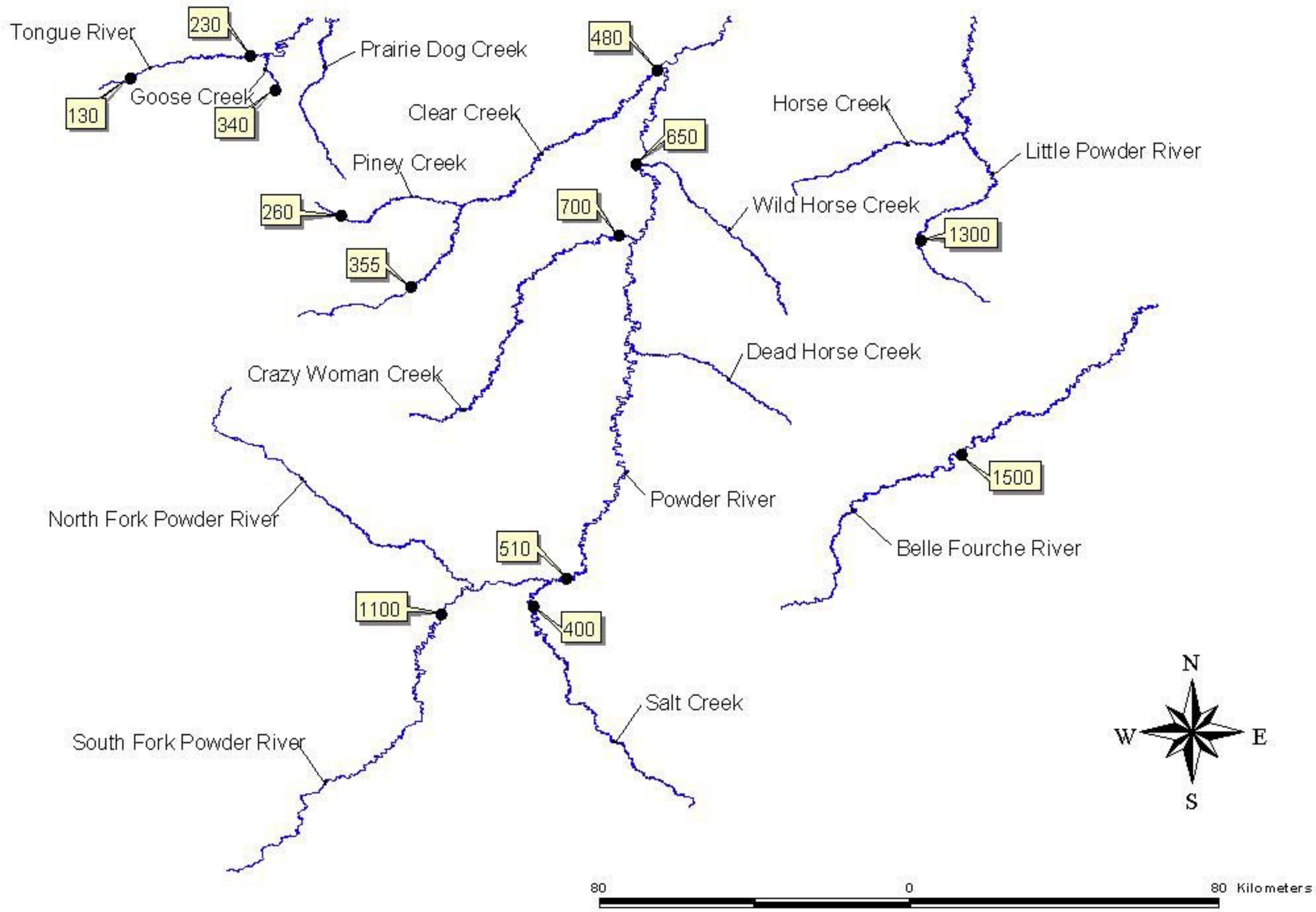

Figure 10. Median hardness values (mg/L as $CaCO_3$) in surface waters of the Powder River Basin of Wyoming, measured at USGS gauging stations from 1951 until 1999. Refer to Tables 1 and 2 for details about the locations of the gauging stations.

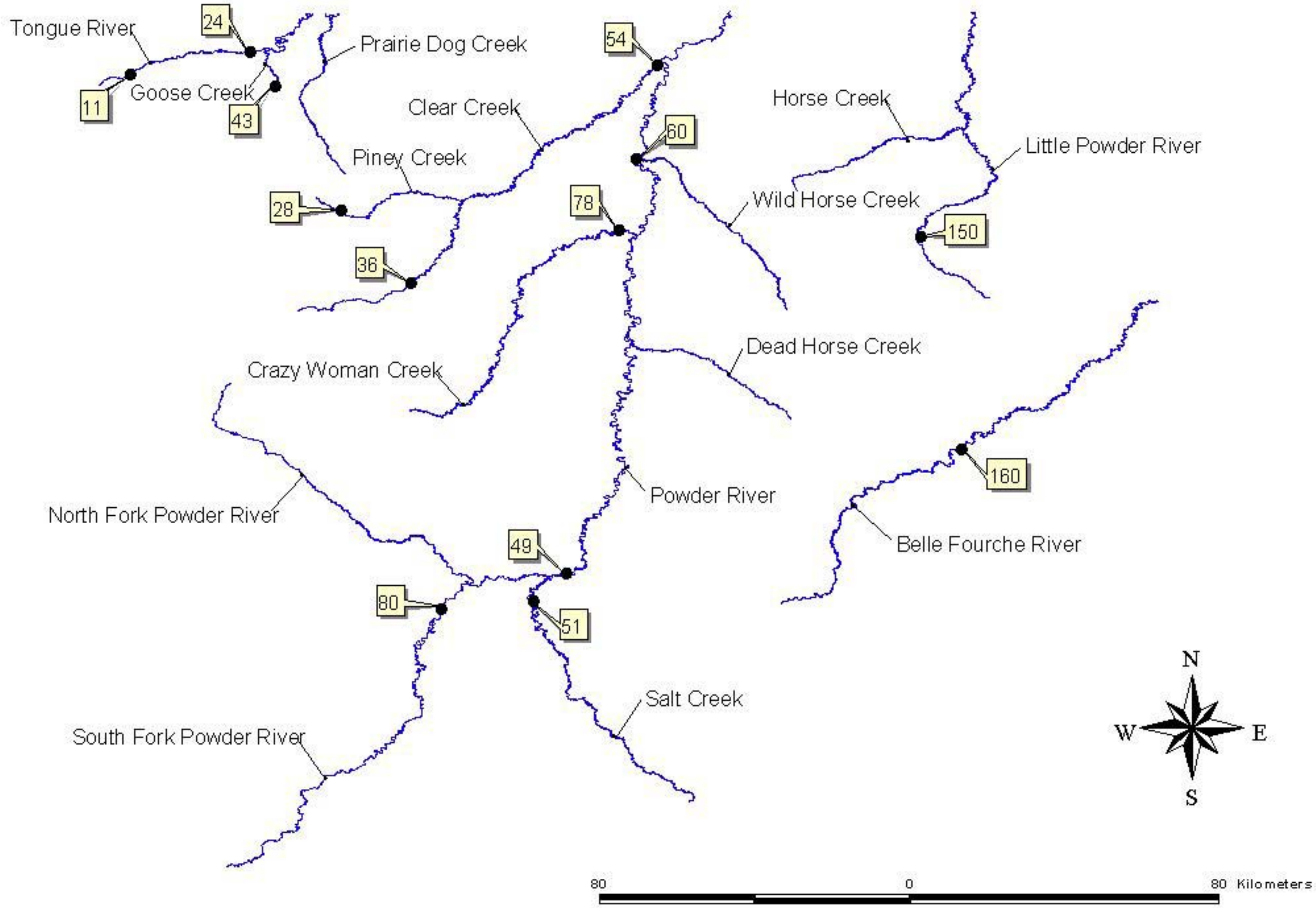

Figure 11. Median magnesium concentrations (mg/L) in surface waters of the Powder River Basin of Wyoming, measured at USGS gauging stations from 1951 until 1999. Refer to Tables 1 and 2 for details about the locations of the gauging stations.

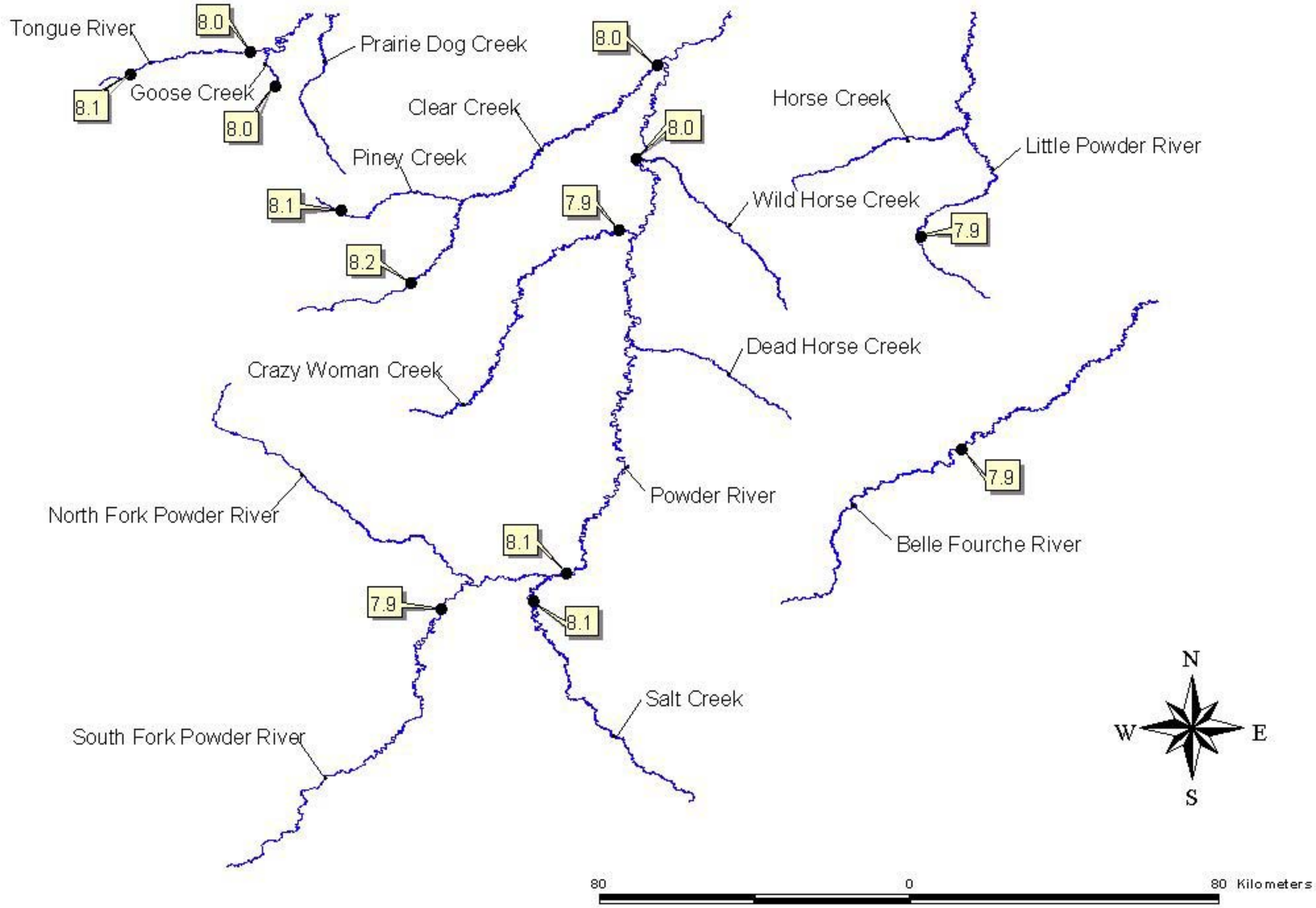

Figure 12. Median pH values (standard units) in surface waters of the Powder River Basin of Wyoming, measured at USGS gauging stations from 1951 until 1999. Refer to Tables 1 and 2 for details about the locations of the gauging stations.

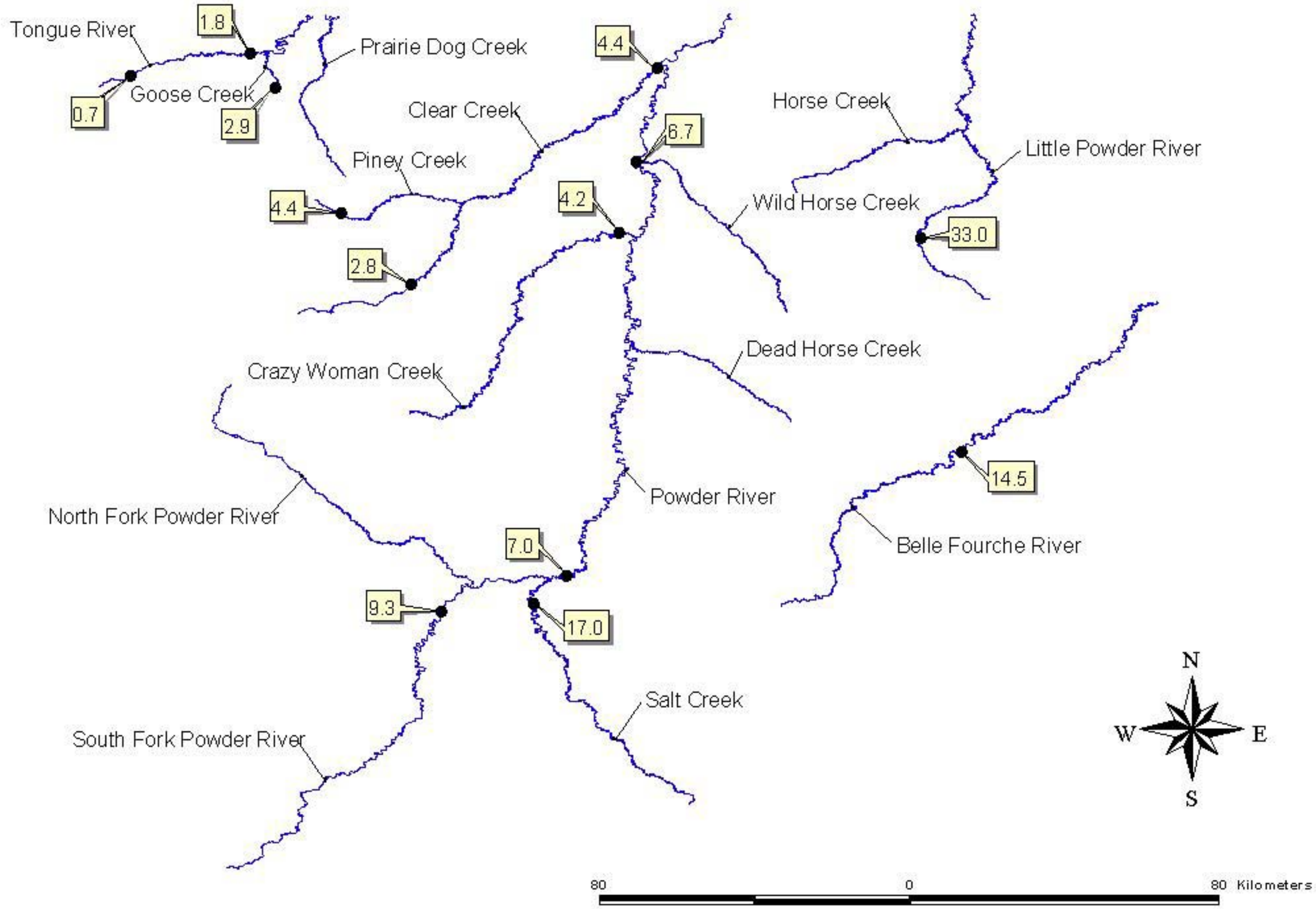

Figure 13. Median potassium concentrations (mg/L) in surface waters of the Powder River Basin of Wyoming, measured at USGS gauging stations from 1951 until 1999. Refer to Tables 1 and 2 for details about the locations of the gauging stations.

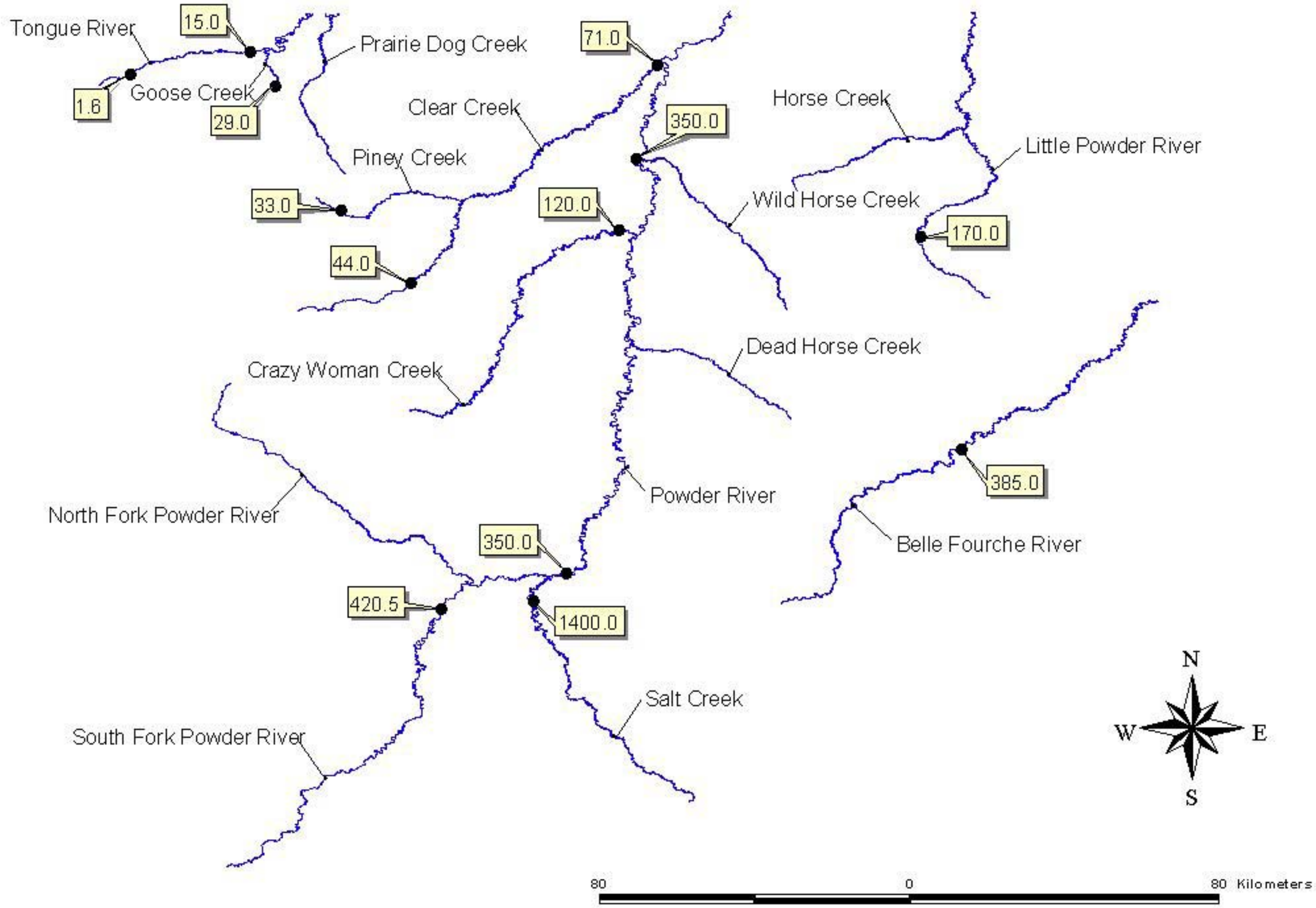

Figure 14. Median sodium concentrations (mg/L) in surface waters of the Powder River Basin of Wyoming, measured at USGS gauging stations from 1951 until 1999. Refer to Tables 1 and 2 for details about the locations of the gauging stations.

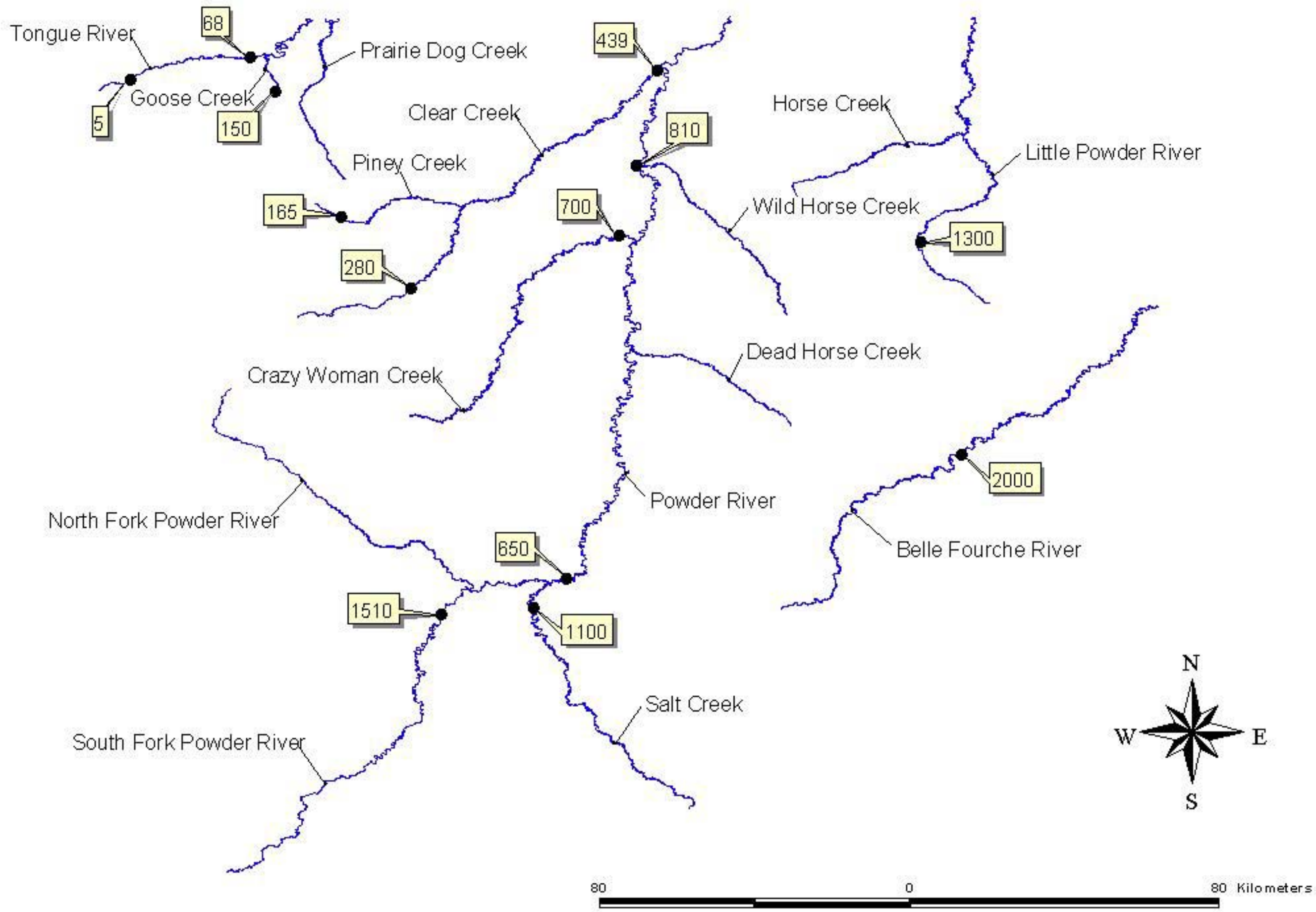

Figure 15. Median sulfate concentrations (mg/L) in surface waters of the Powder River Basin of Wyoming, measured at USGS gauging stations from 1951 until 1999. Refer to Tables 1 and 2 for details about the locations of the gauging stations.

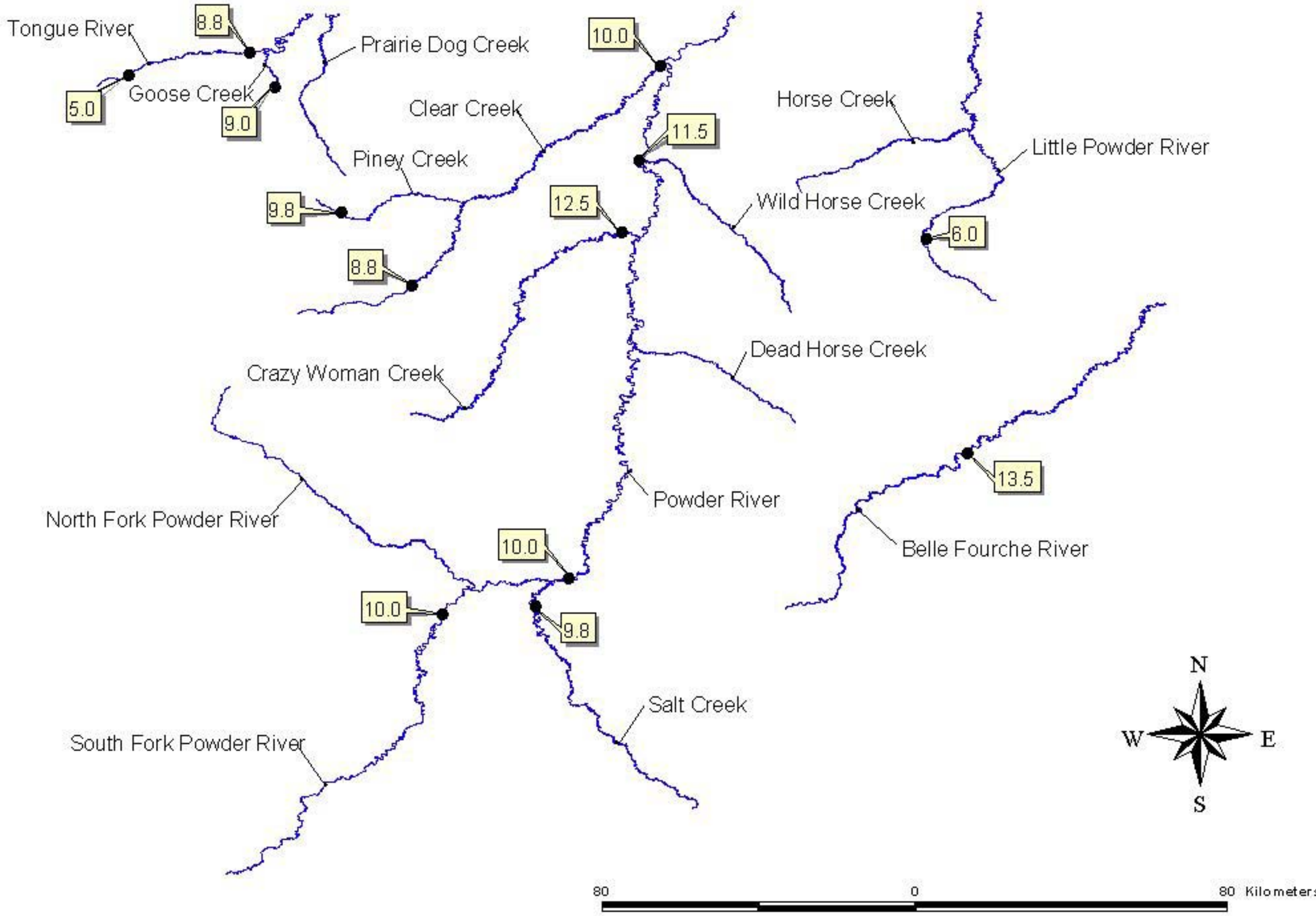

Figure 16. Median temperatures (°C) in surface waters of the Powder River Basin of Wyoming, measured at USGS gauging stations from 1951 until 1999. Refer to Tables 1 and 2 for details about the locations of the gauging stations.

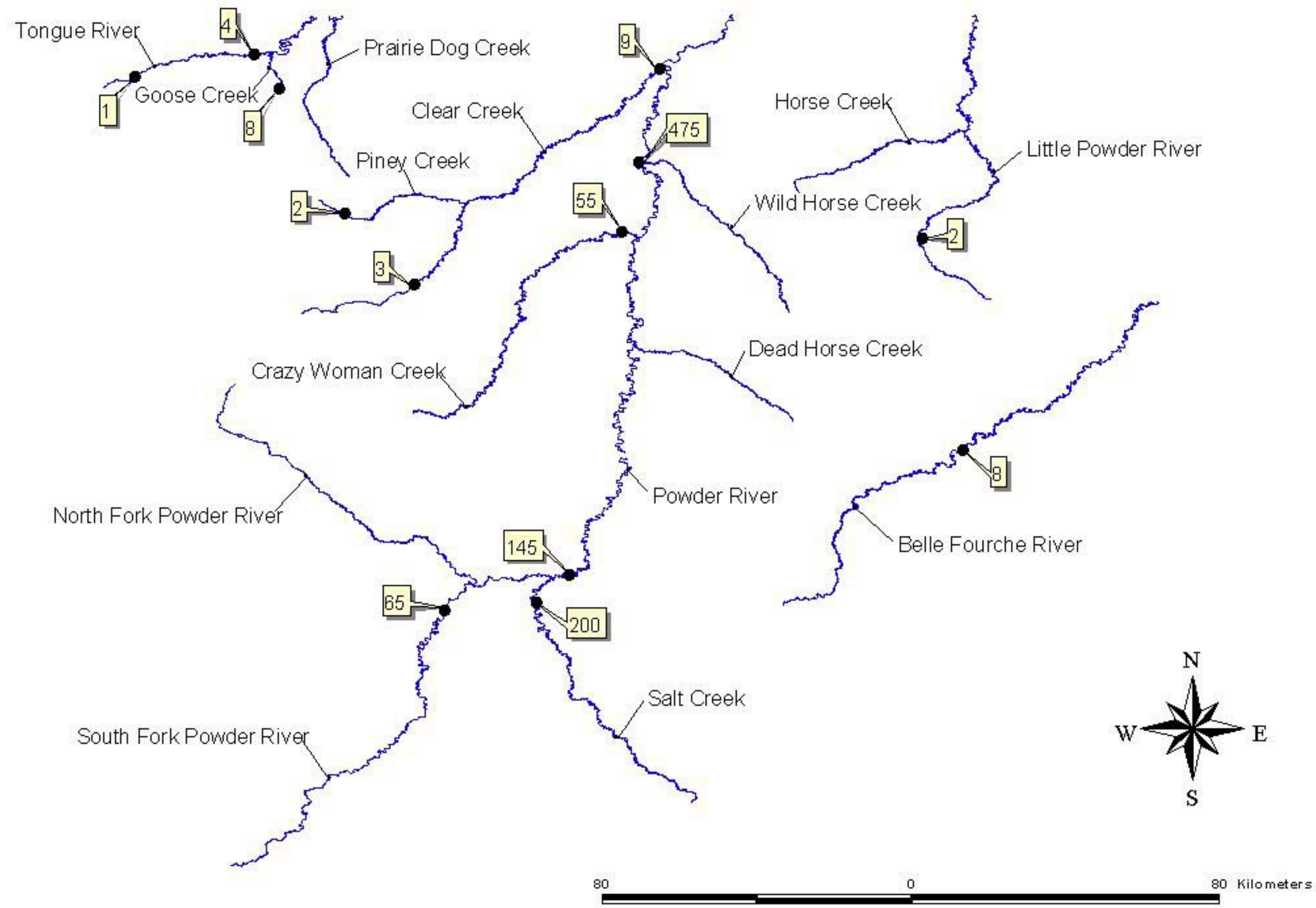

Figure 17. Median turbidity values (Jackson Candle Units -- JCUs) in surface waters of the Powder River Basin of Wyoming, measured at USGS gauging stations from 1951 until 1999. Refer to Tables 1 and 2 for details about the locations of the gauging stations.

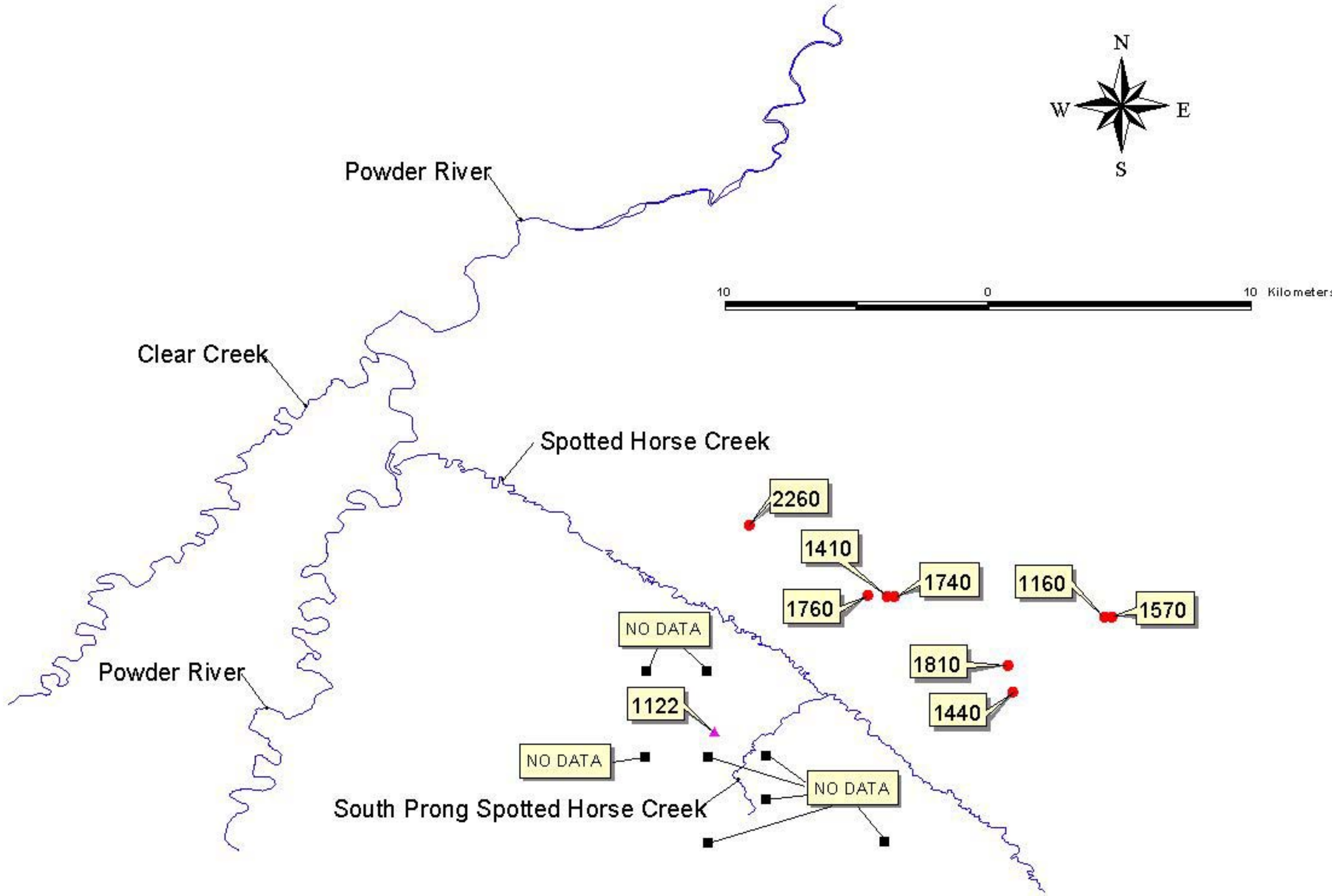

Figure 18. Alkalinity (mg/L as $CaCO_3$) of product water from coalbed methane wells in the northern portion of the Powder River drainage, including Clear and Spotted Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

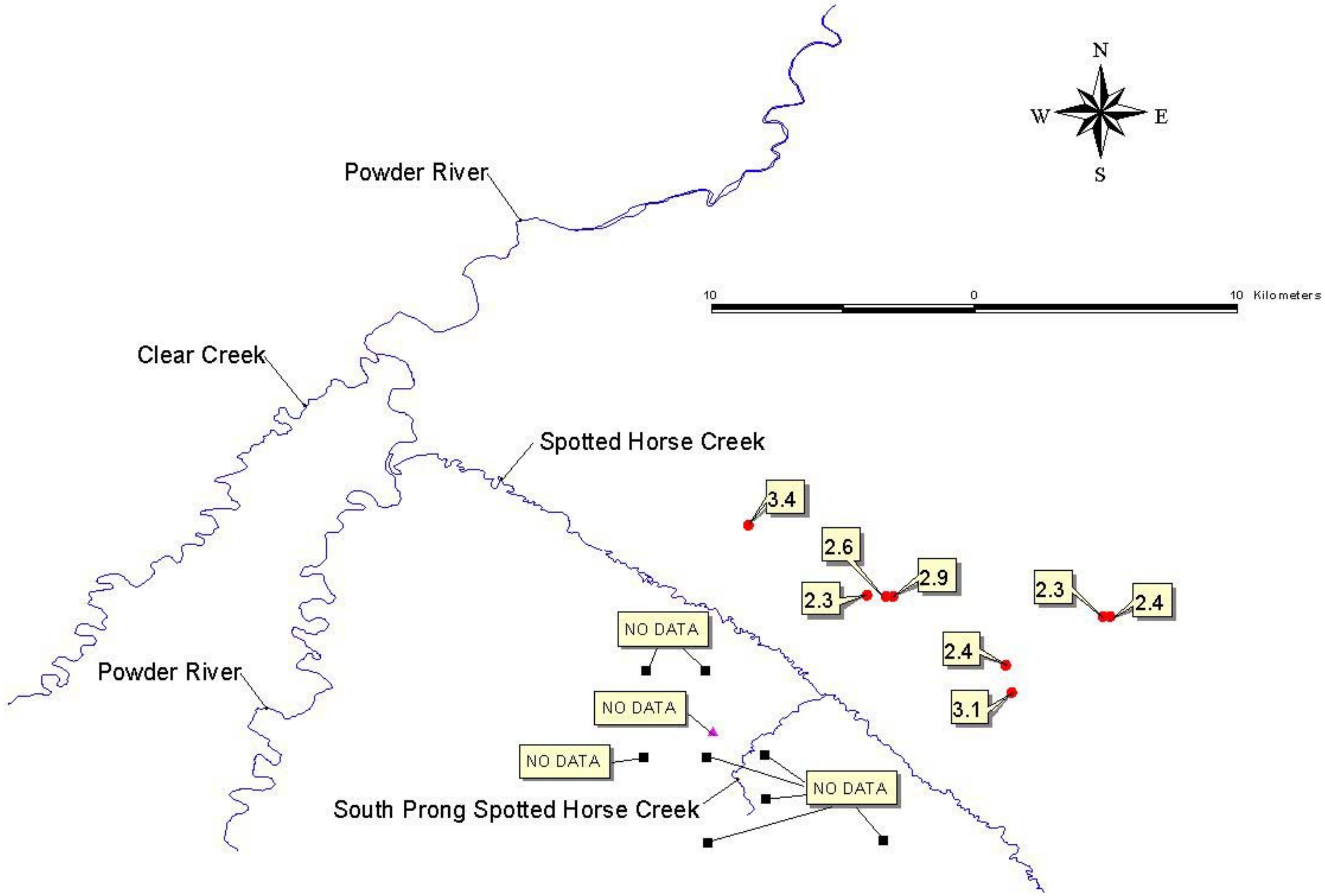

Figure 19. Ammonia concentrations (mg NH_4^+/L) in product water from coalbed methane wells in the northern portion of the Powder River drainage, including Creek and Spotted Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

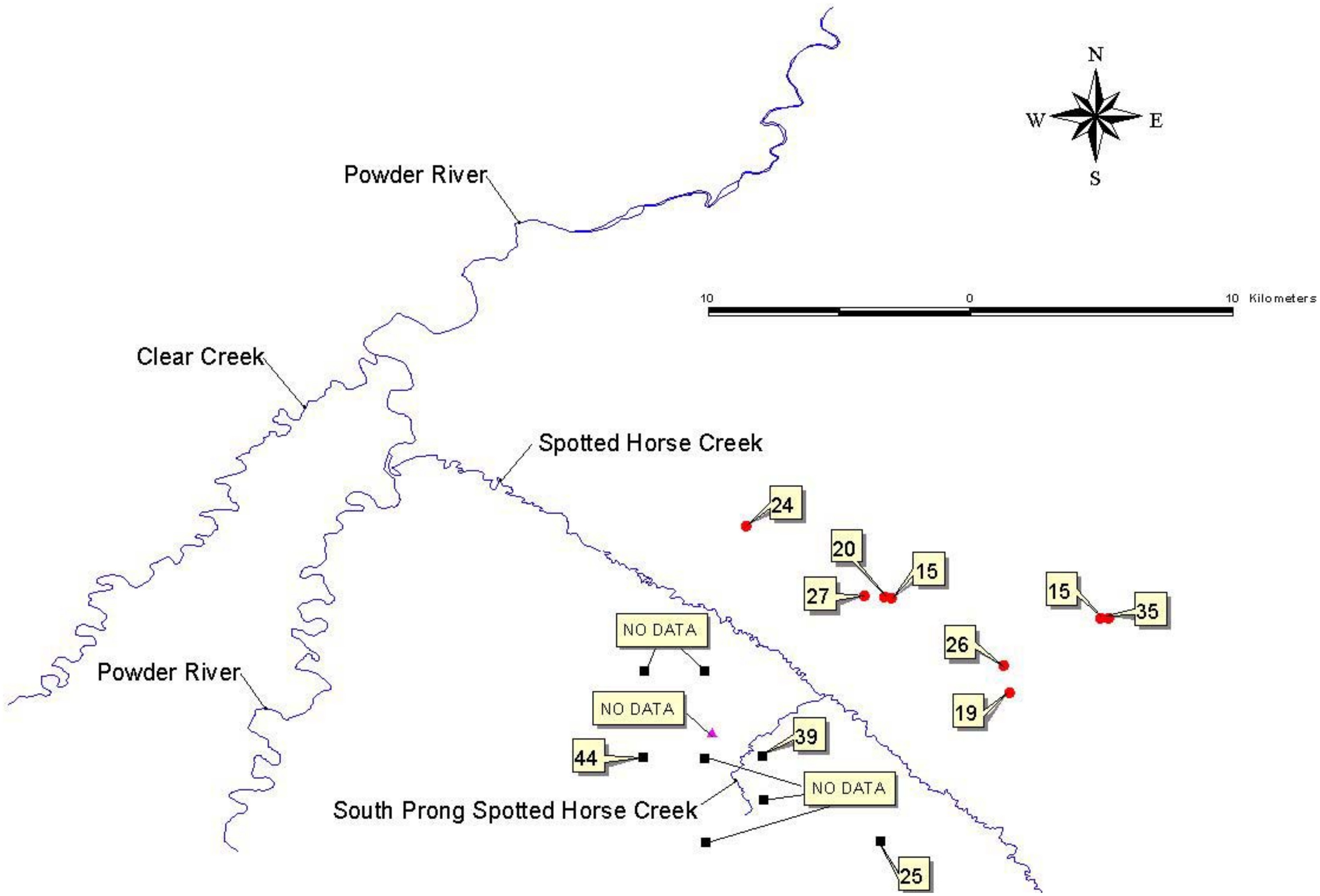

Figure 20. Calcium concentrations (mg/L) in product water from coalbed methane wells in the northern portion of the Powder River drainage, including Clear and Spotted Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

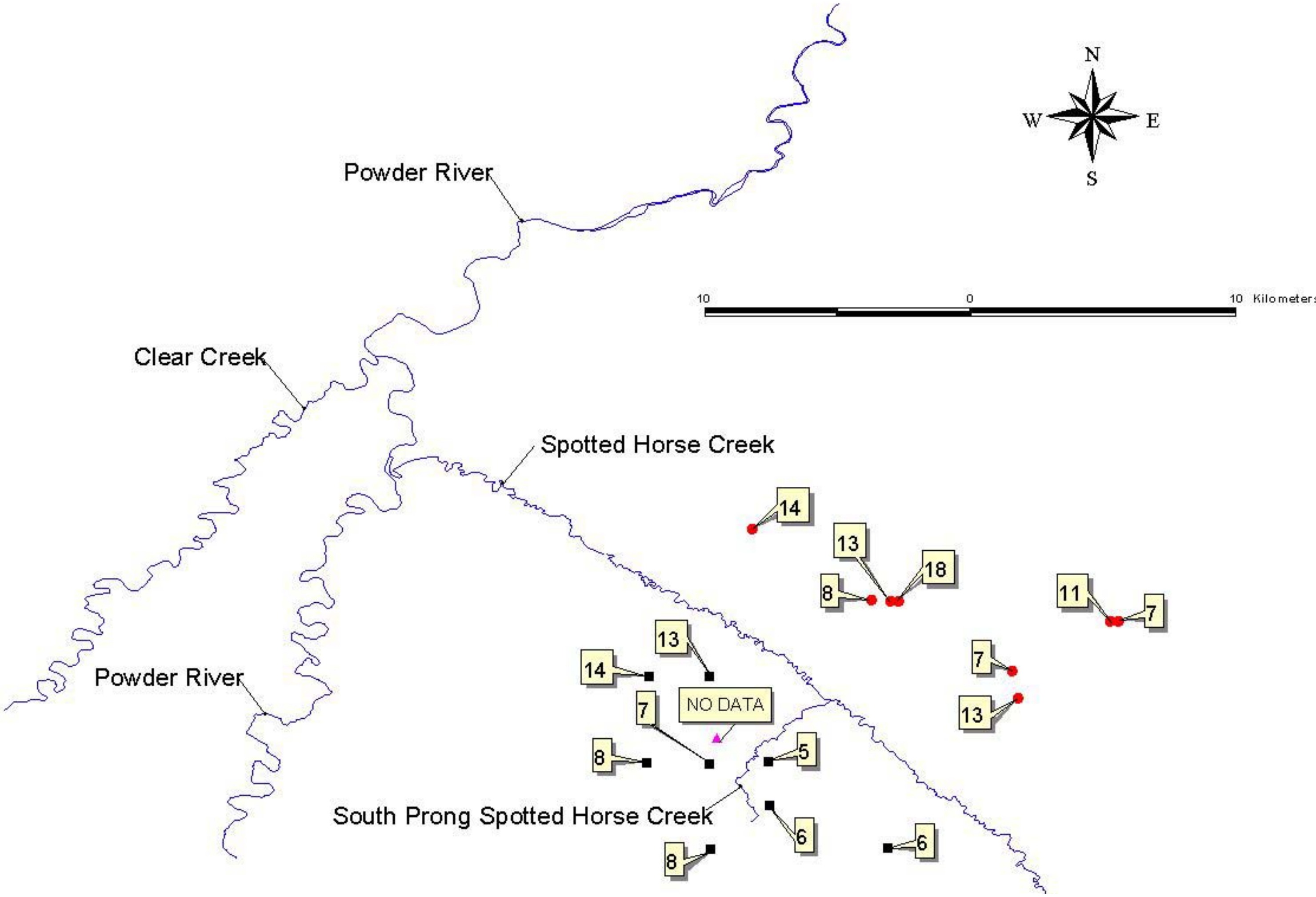

Figure 21. Chloride concentrations (mg/L) in product water from coalbed methane wells in the northern portion of the Powder River drainage, including Clear and Spotted Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

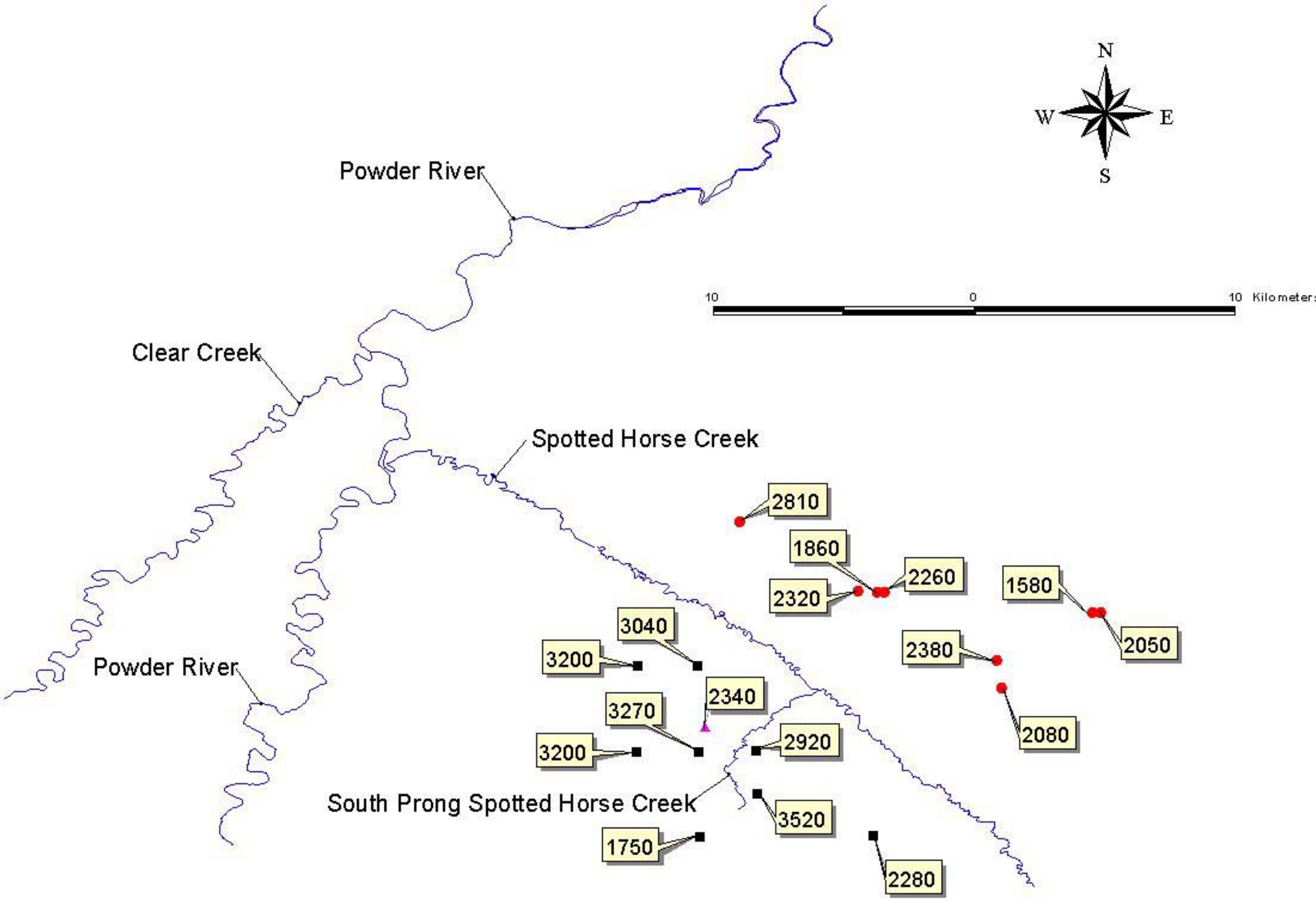

Figure 22. Conductivity (μS/cm) of product water from coalbed methane wells in the northern portion of the Powder River drainage, including Clear and Spotted Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

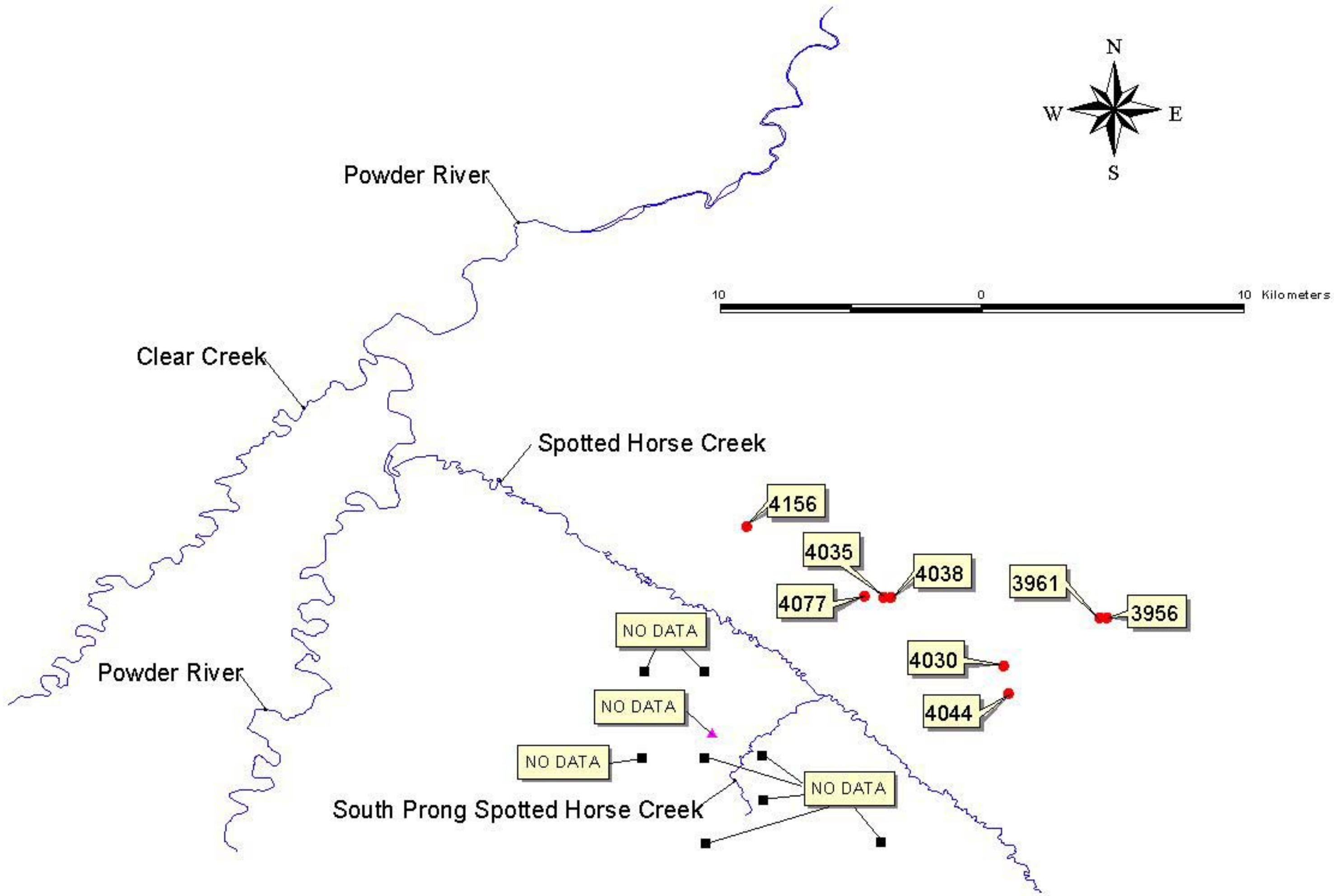

Figure 23. Depth (ft) of coalbed methane wells in the northern portion of the Powder River drainage, including Clear and Spotted Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

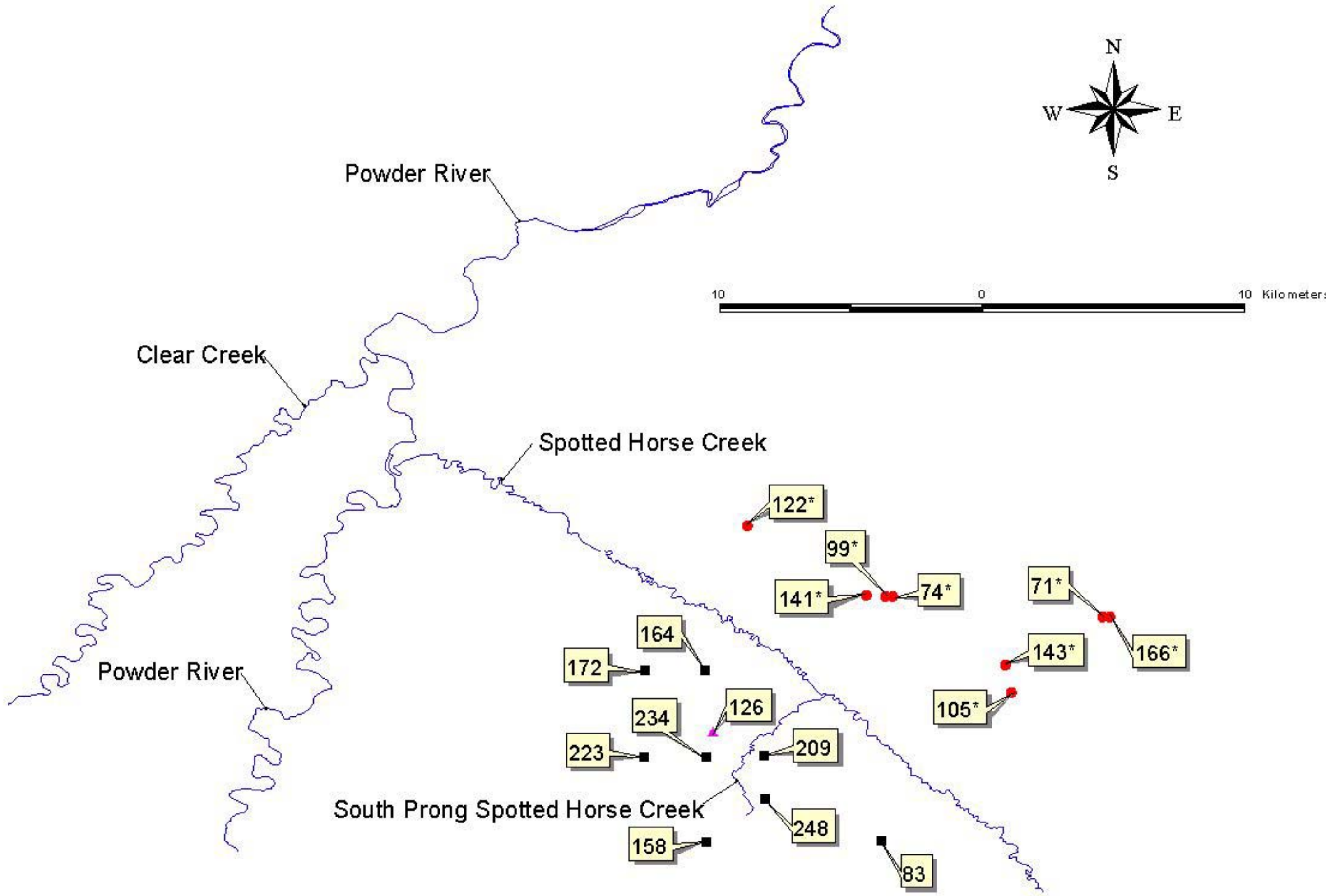

Figure 24. Hardness (mg/L as $CaCO_3$; * indicates values calculated from sum of mEq/L of Ca and Mg) of product water from coalbed methane wells in the northern portion of the Powder River drainage, including Clear and Spotted Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

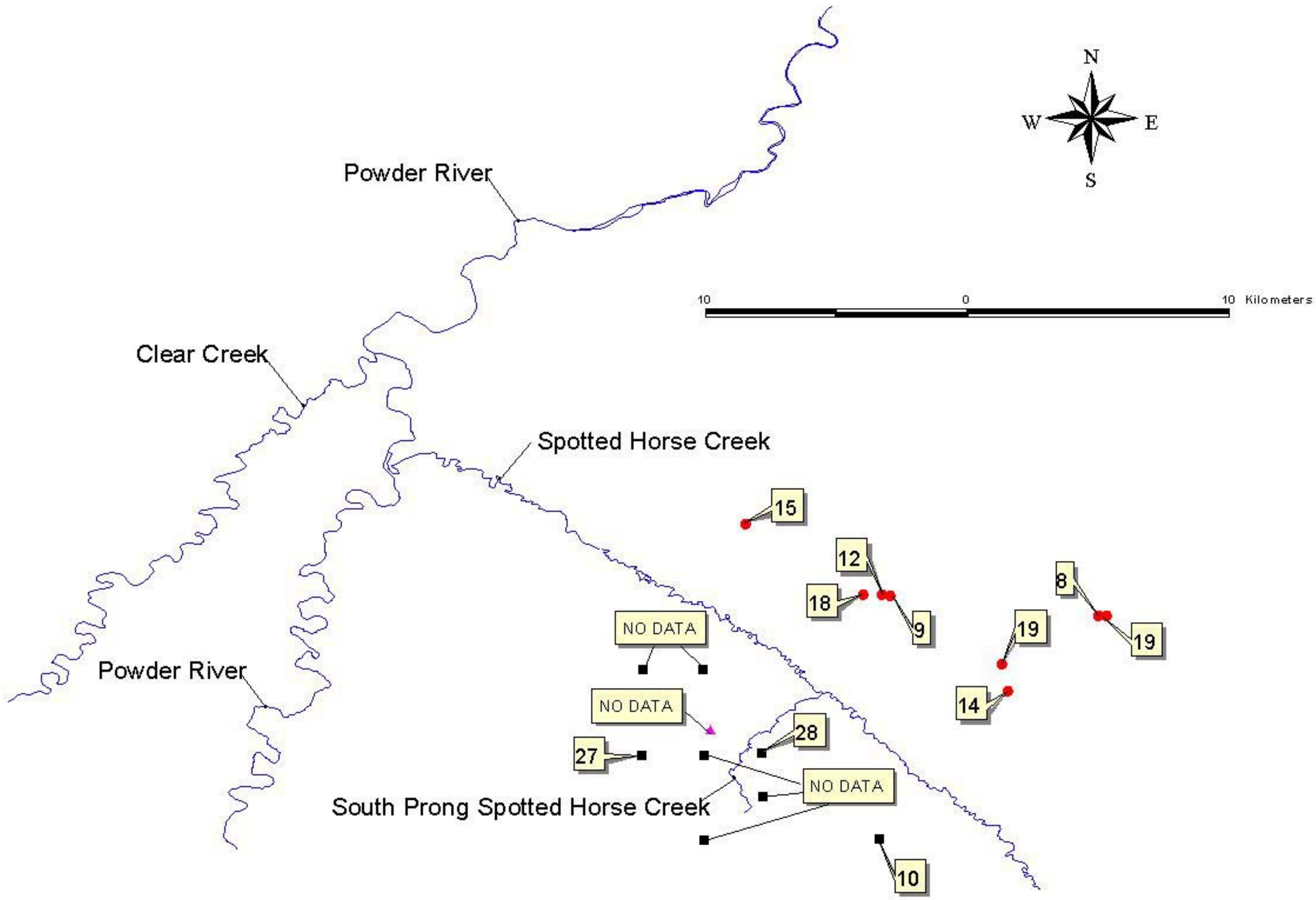

Figure 25. Magnesium concentrations (mg/L) in product water from coalbed methane wells in the northern portion of the Powder River drainage, including Clear and Spotted Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

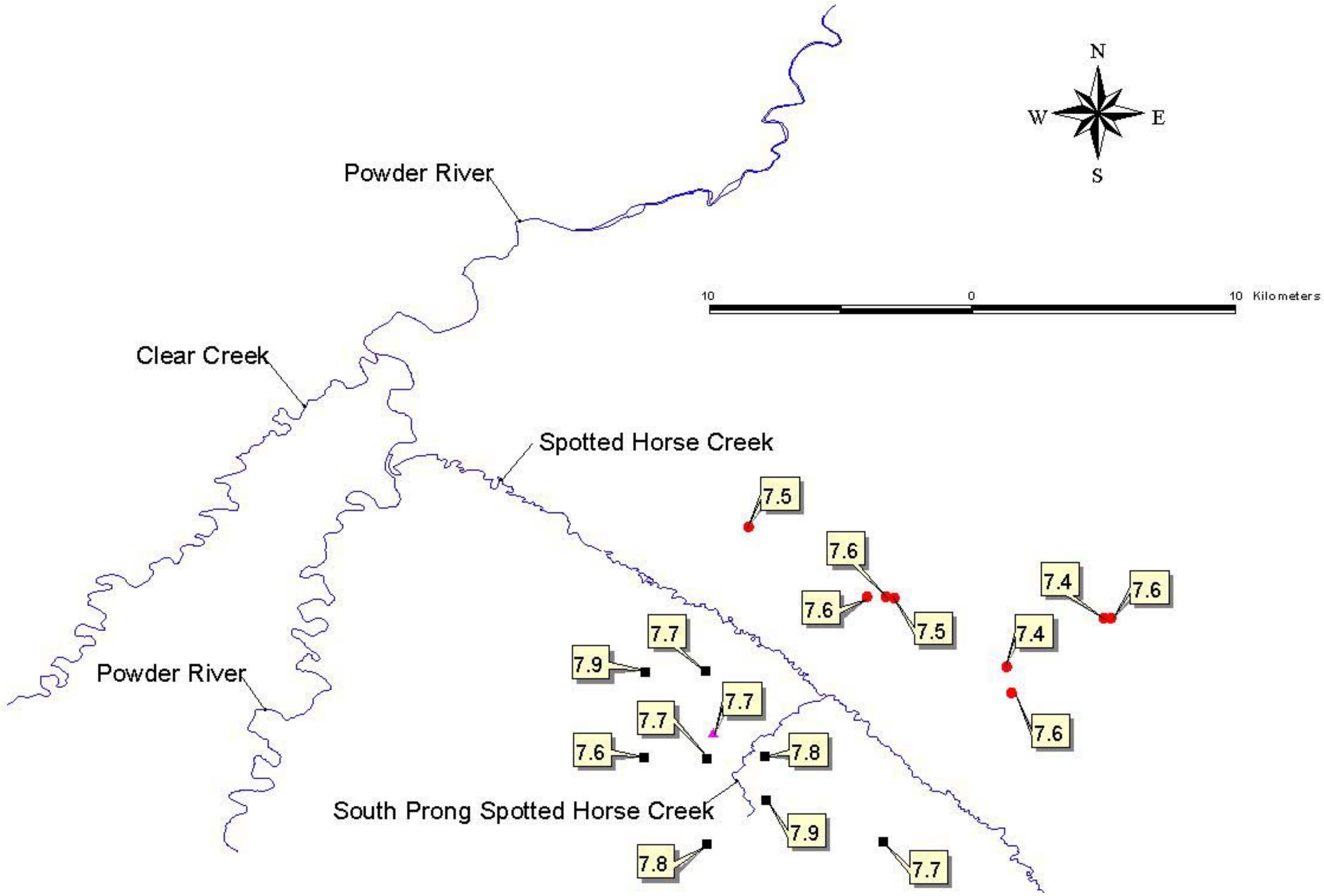

Figure 26. pH (standard units) of product water from coalbed methane wells in the northern portion of the Powder River drainage, including Clear and Spotted Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

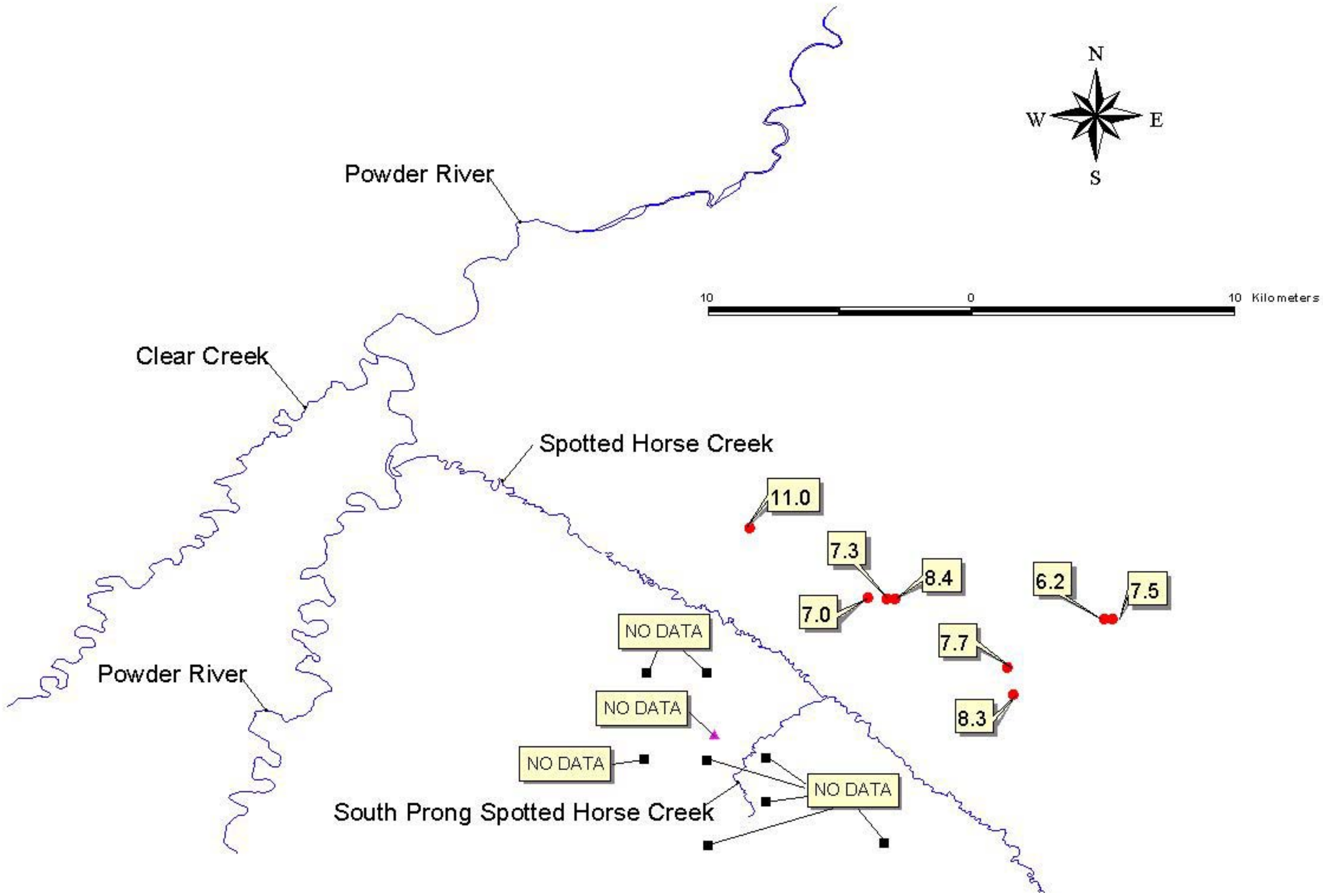

Figure 27. Potassium concentrations (mg/L) in product water from coalbed methane wells in the northern portion of the Powder River drainage, including Clear and Spotted Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

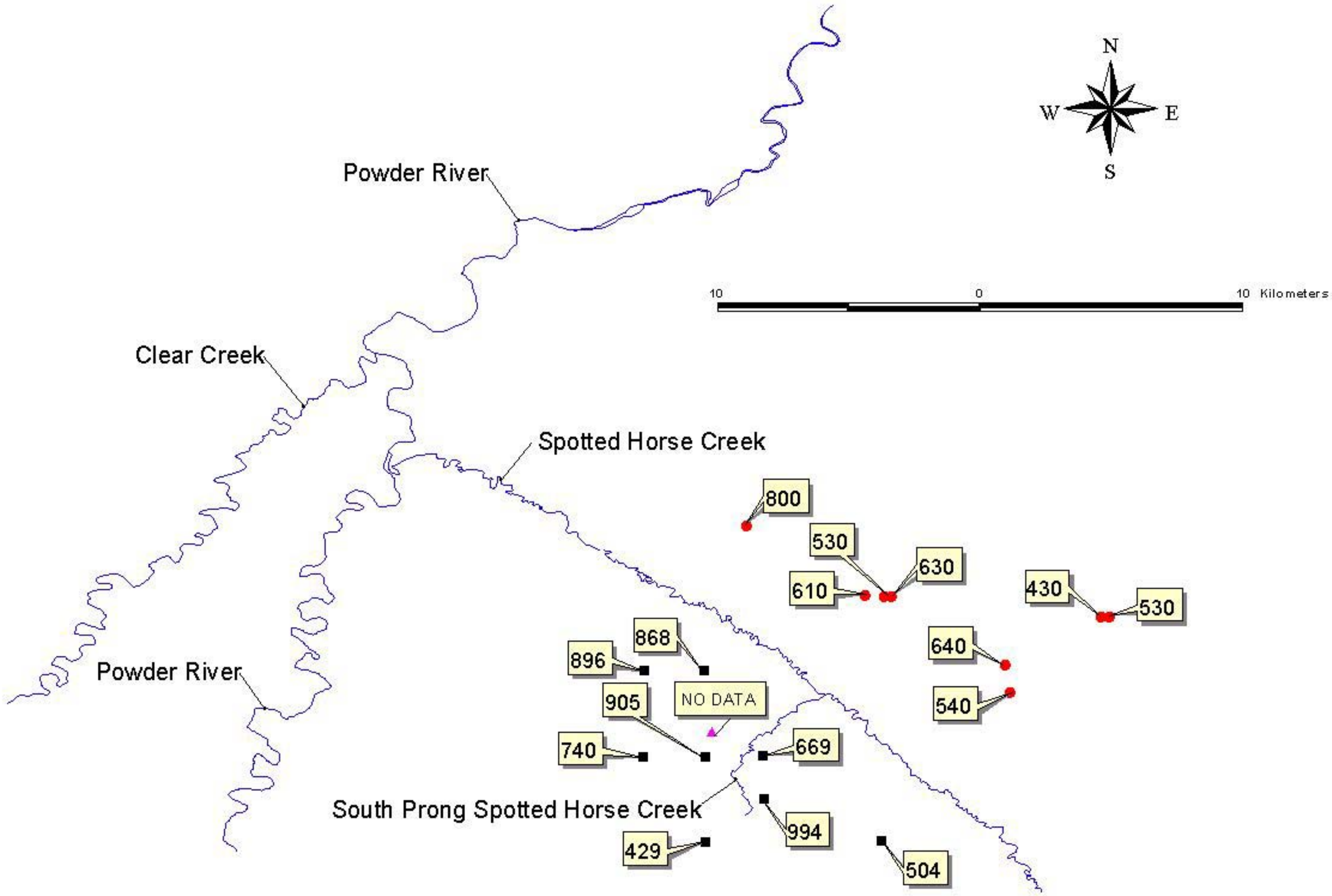

Figure 28. Sodium concentrations (mg/L) in product water from coalbed methane wells in the northern portion of the Powder River drainage, including Clear and Spotted Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

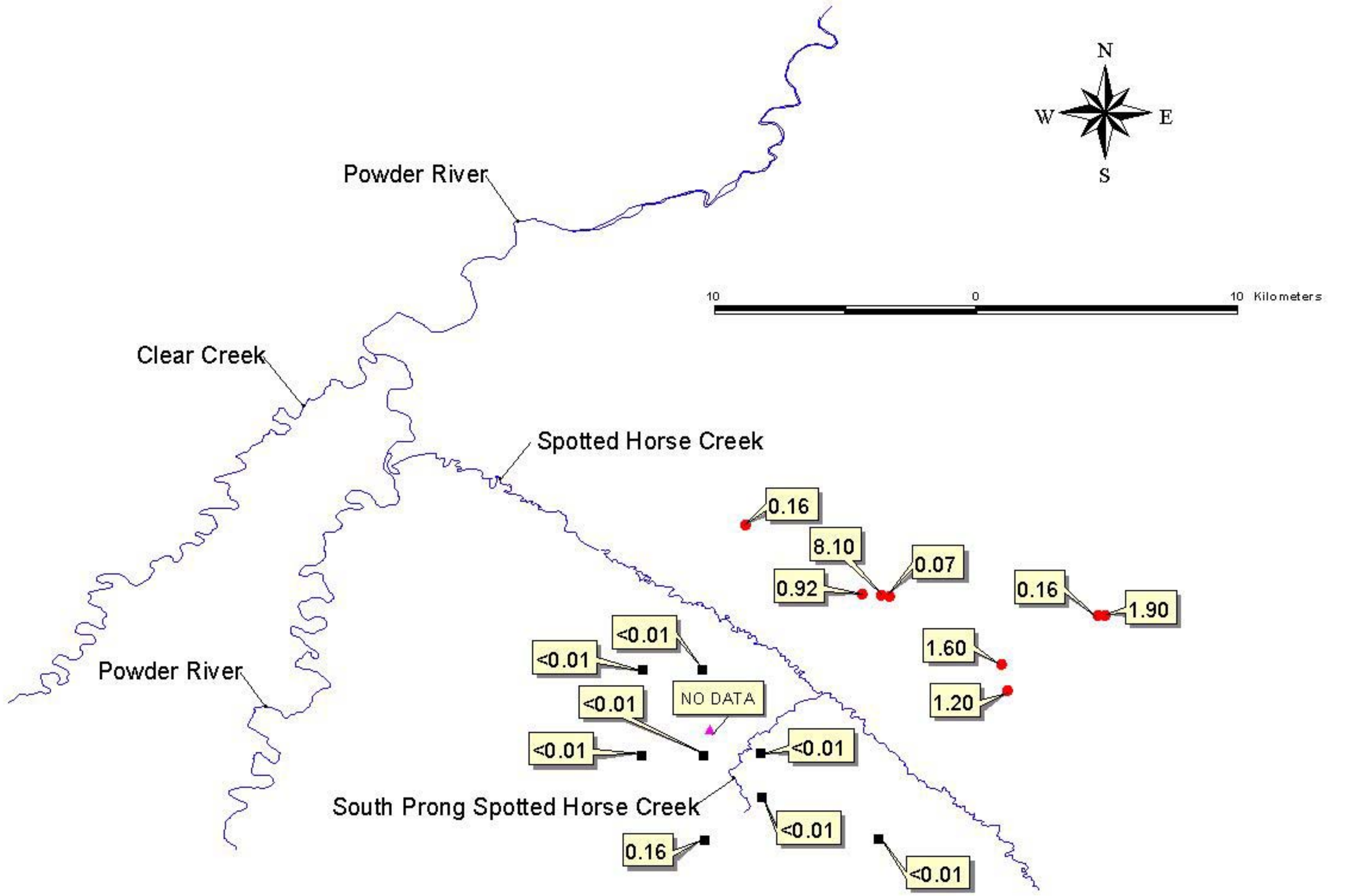

Figure 29. Sulfate concentrations (mg/L) in product water from coalbed methane wells in the northern portion of the Powder River drainage, including Clear and Spotted Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

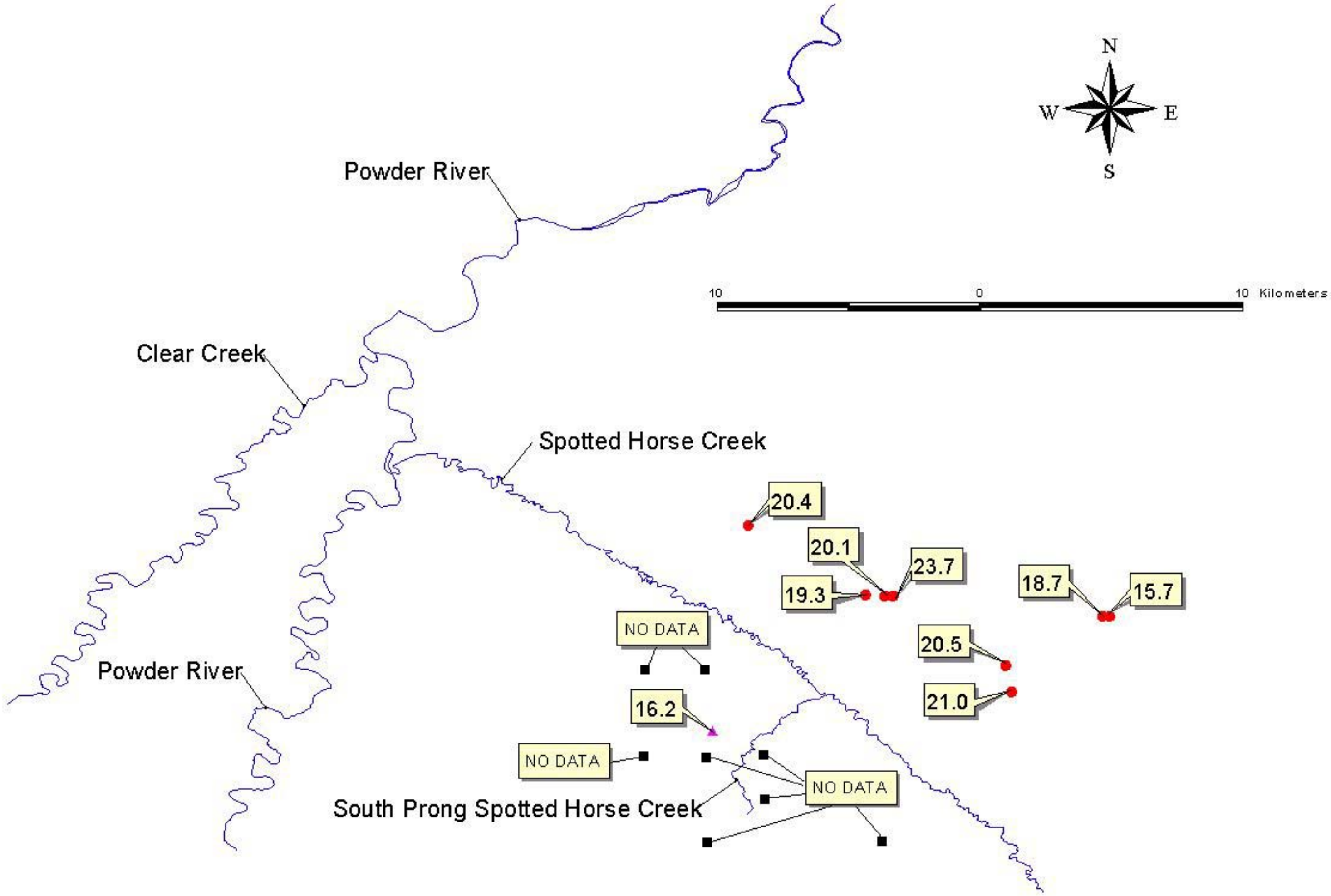

Figure 30. Temperatures (°C) of product water from coalbed methane wells in the northern portion of the Powder River drainage, including Clear and Spotted Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

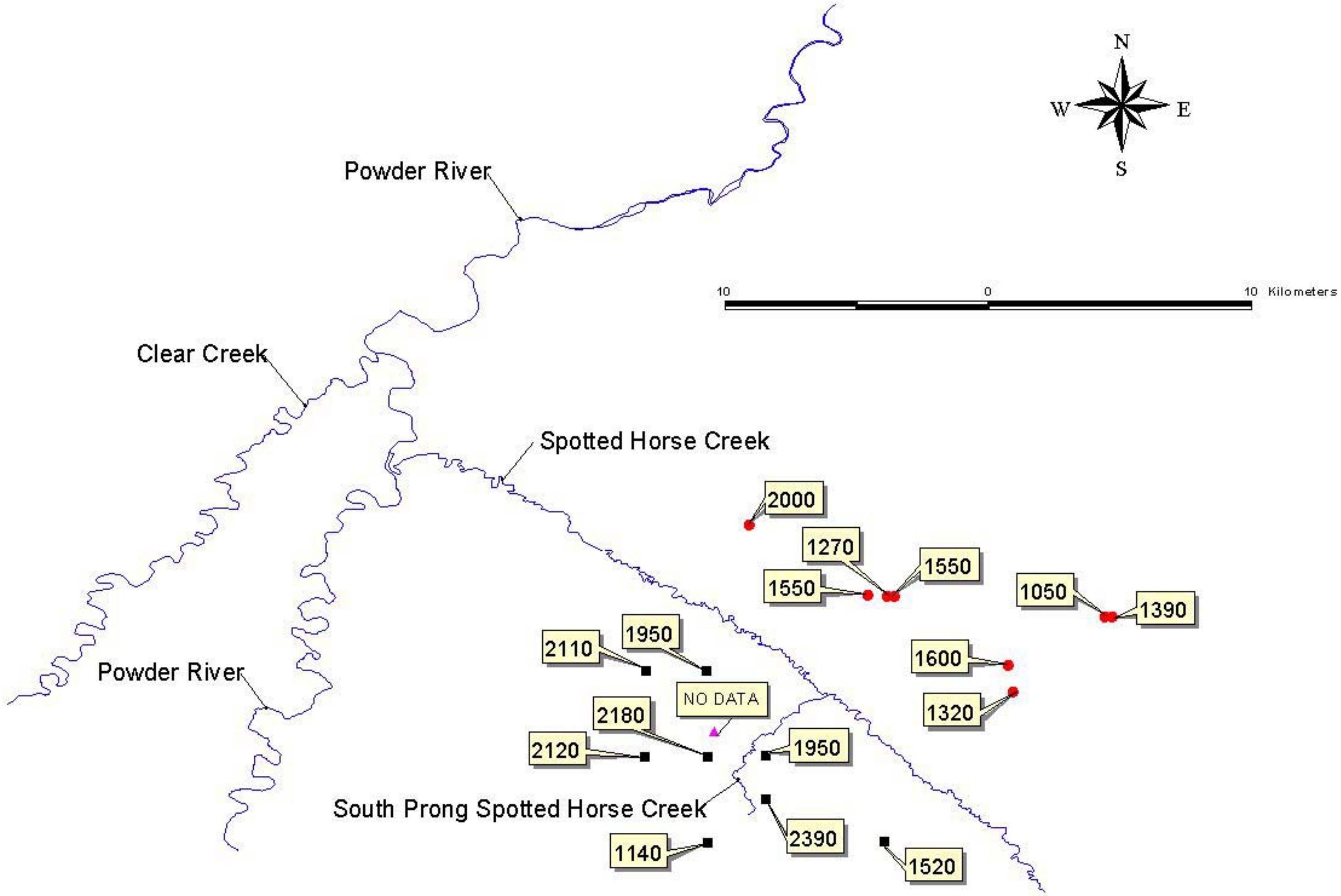

Figure 31. Total dissolved solids concentrations (mg/L) in product water from coalbed methane wells in the northern portion of the Powder River drainage, including Clear and Spotted Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

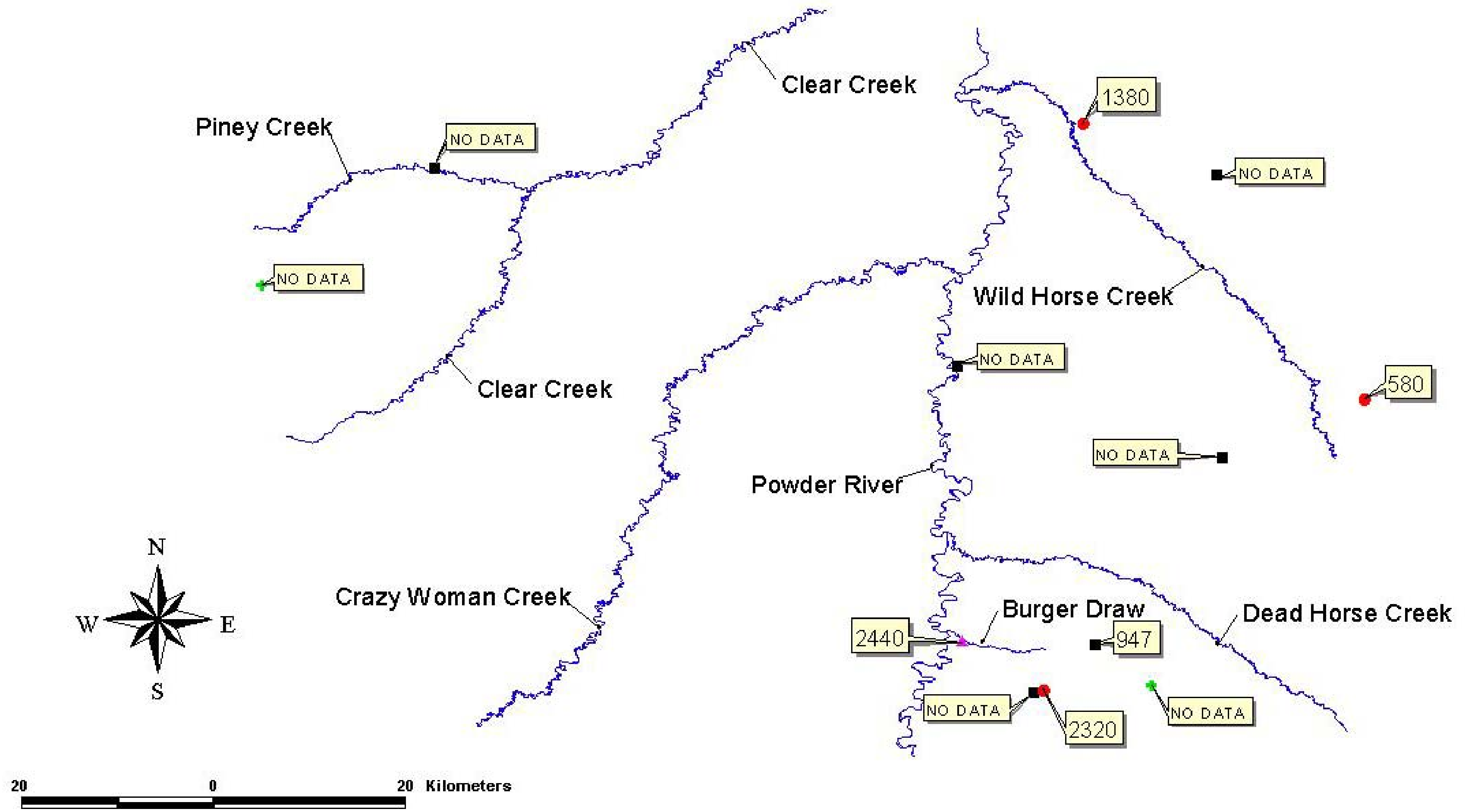

Figure 32. Alkalinity (mg/L as $CaCO_3$) of product water from coalbed methane wells in the southern portion of the Powder River drainage, including Clear, Piney, Crazy Woman, Dead Horse, and Wild Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

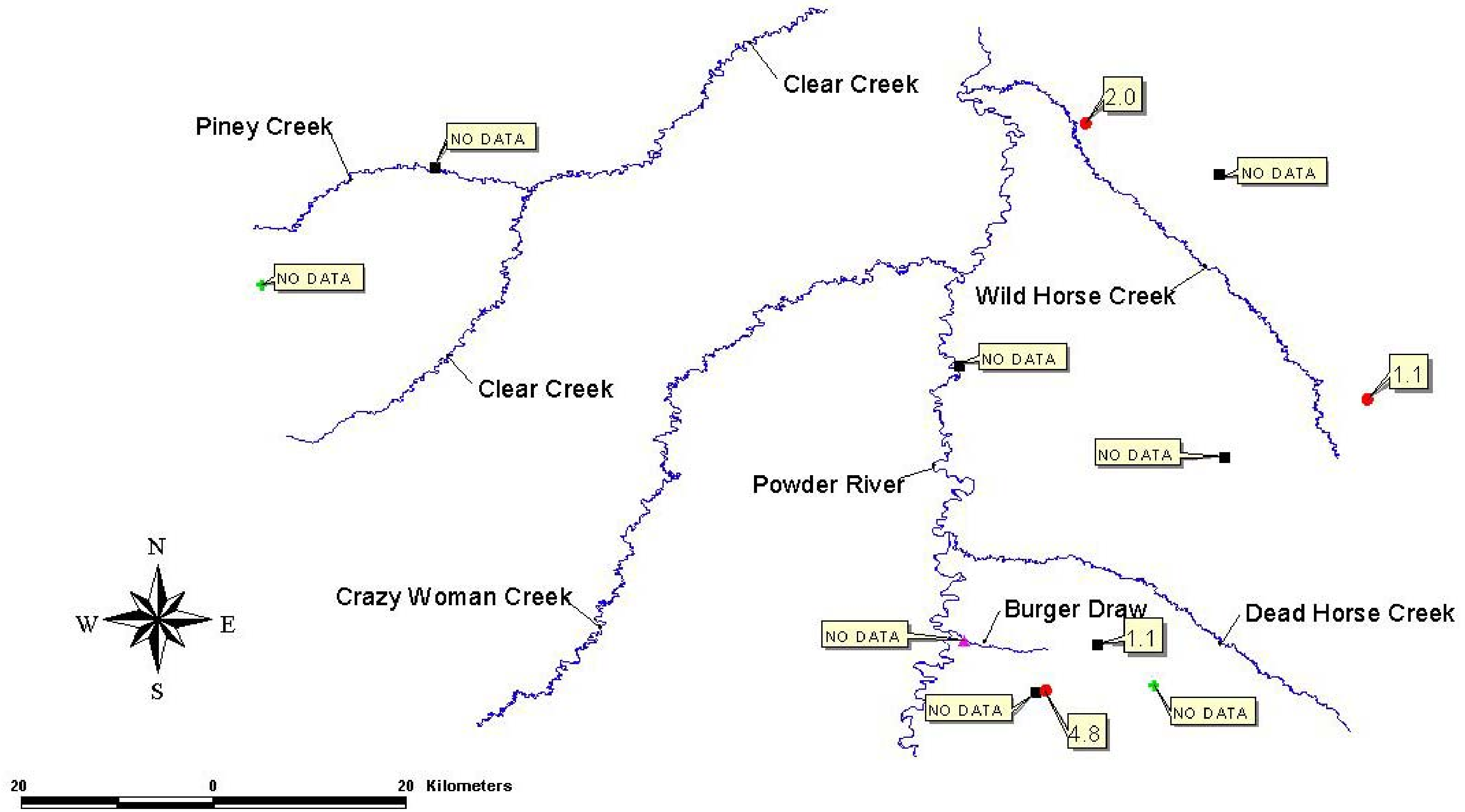

Figure 33. Ammonia concentrations (mg NH_4^+/L) in product water from coalbed methane wells in the southern portion of the Powder River drainage, including Clear, Piney, Crazy Woman, Dead Horse, and Wild Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

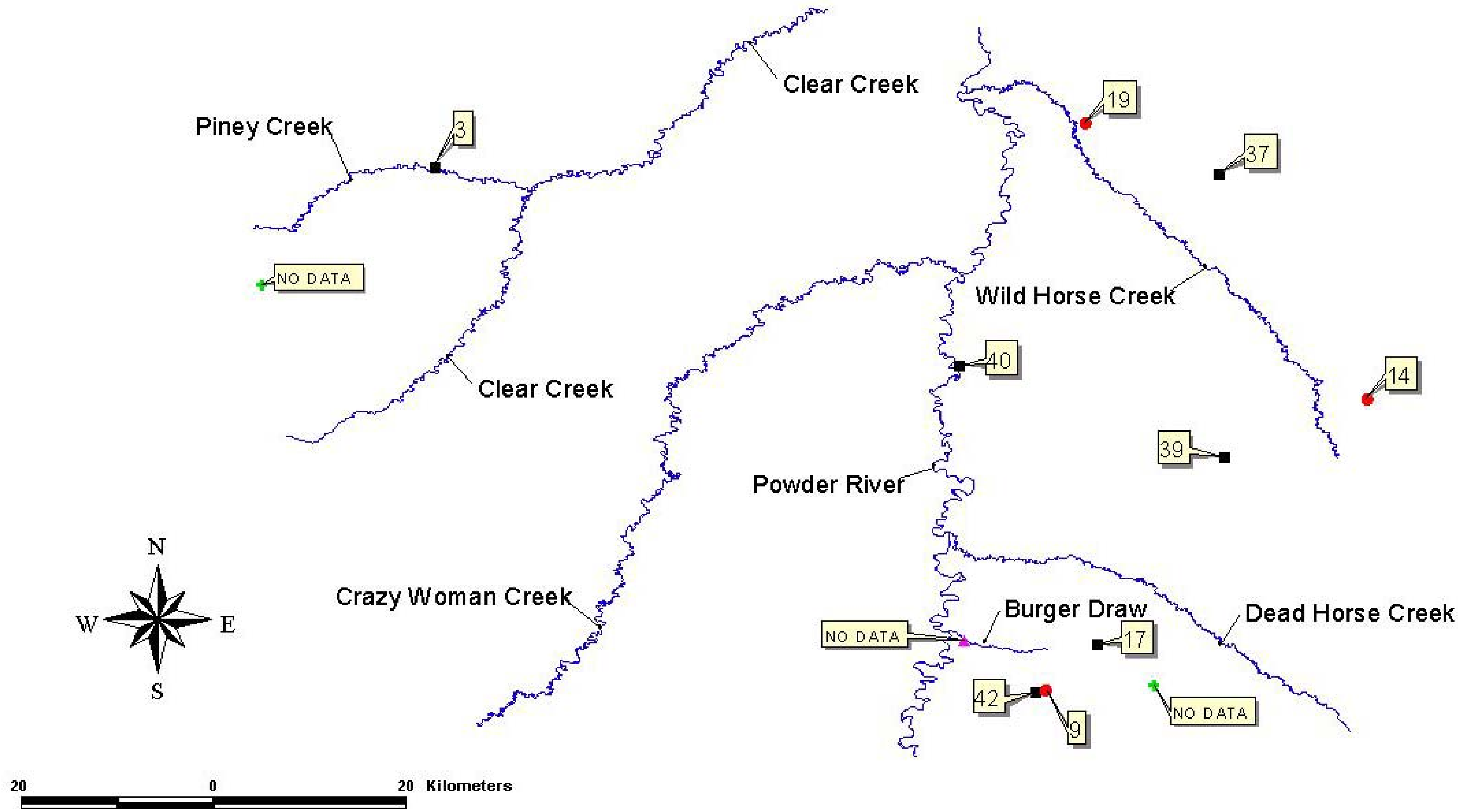

Figure 34. Calcium concentrations (mg/L) in product water from coalbed methane wells in the southern portion of the Powder River drainage, including Clear, Piney, Crazy Woman, Dead Horse, and Wild Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

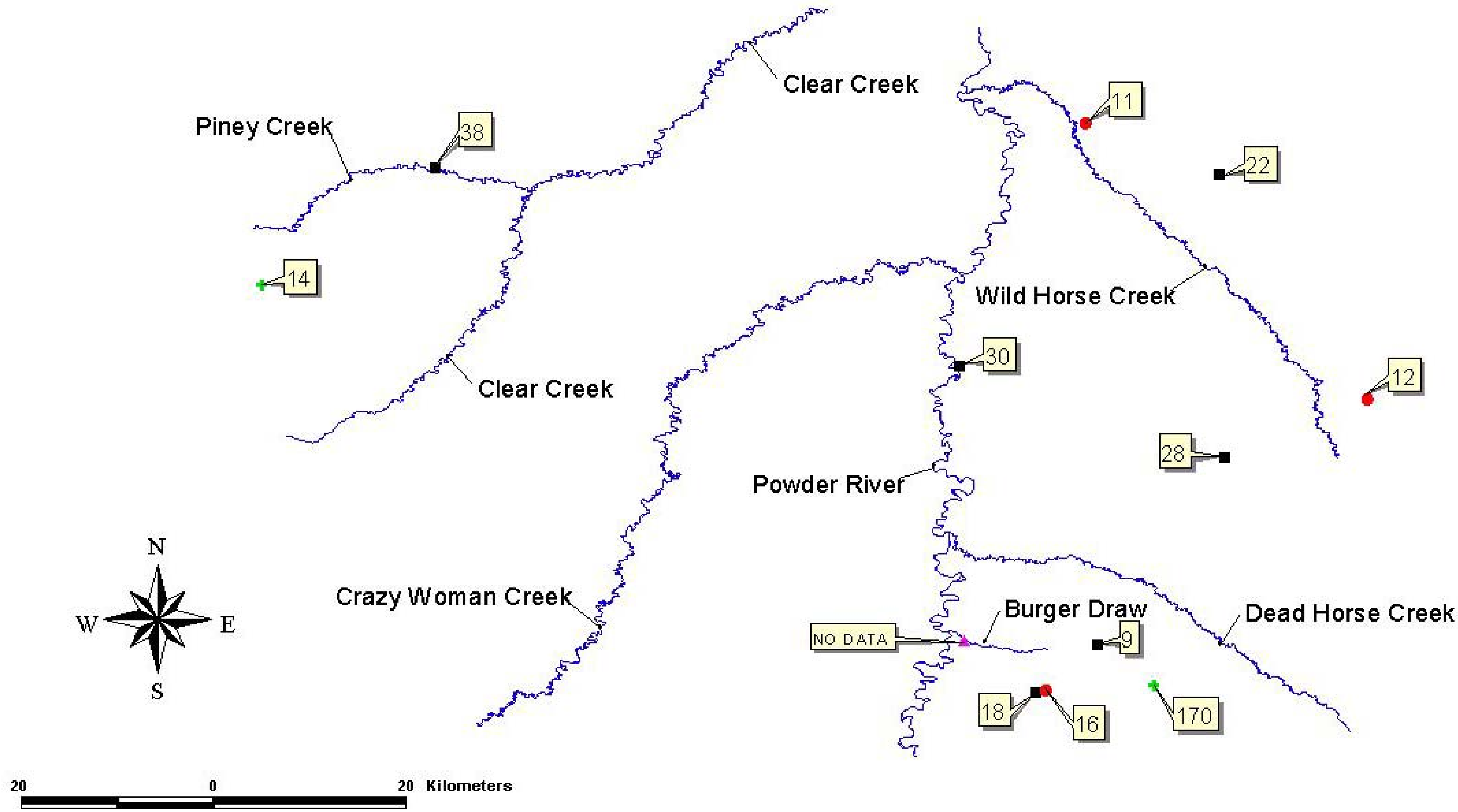

Figure 35. Chloride concentrations (mg/L) in product water from coalbed methane wells in the southern portion of the Powder River drainage, including Clear, Piney, Crazy Woman, Dead Horse, and Wild Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

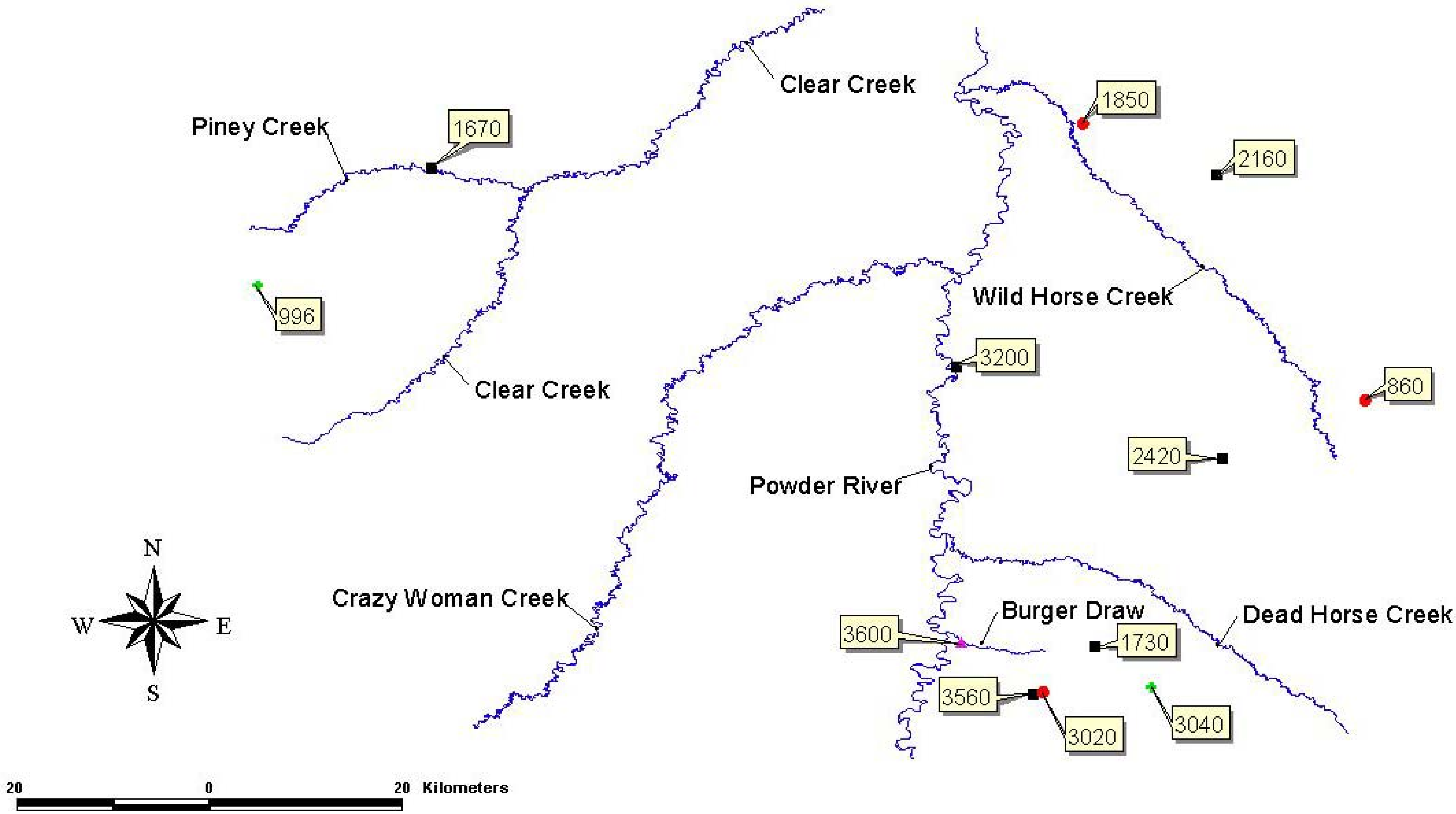

Figure 36. Conductivity (µS/cm) of product water from coalbed methane wells in the southern portion of the Powder River drainage, including Clear, Piney, Crazy Woman, Dead Horse, and Wild Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

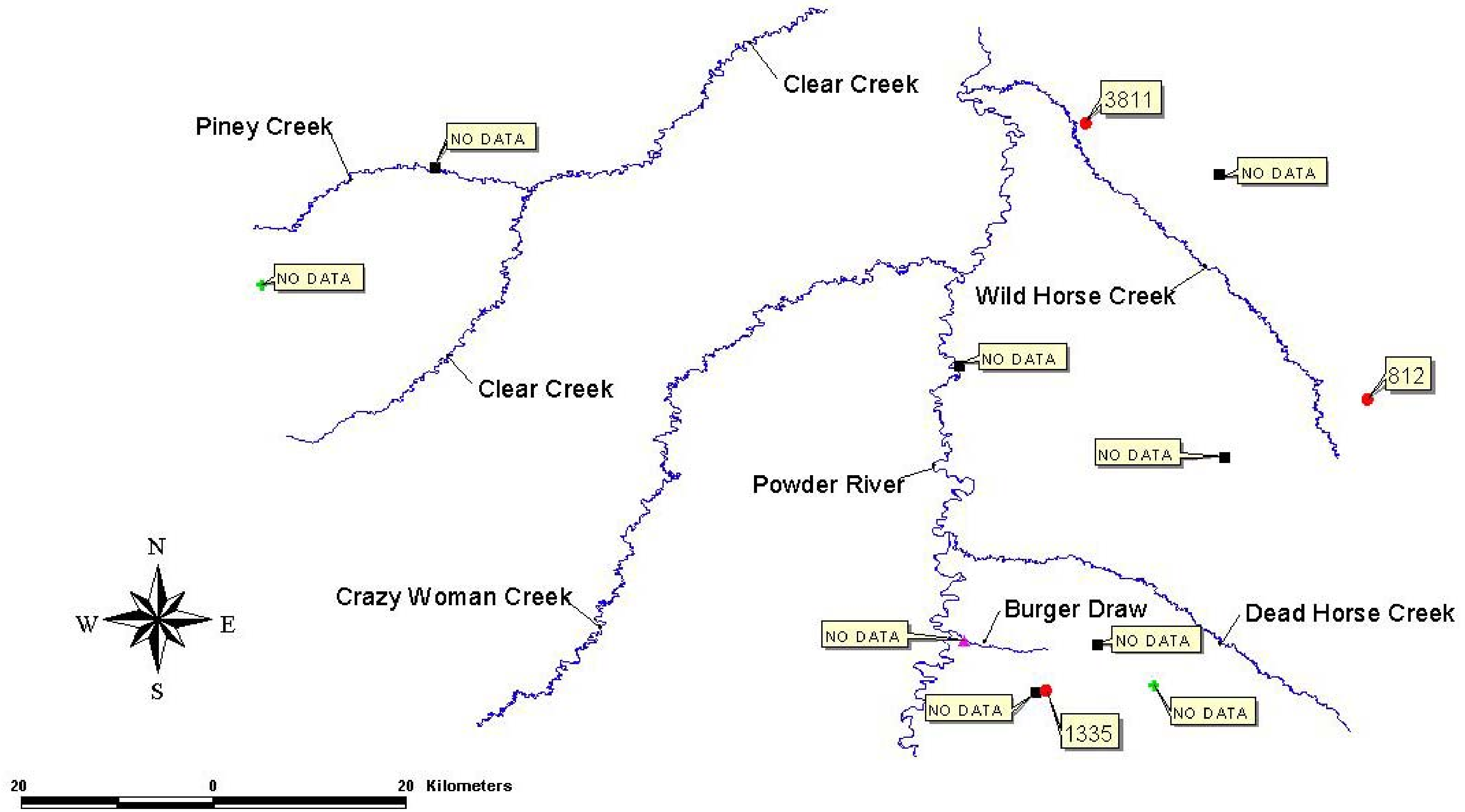

Figure 37. Depth (ft) of coalbed methane wells in the southern portion of the Powder River drainage, including Clear, Piney, Crazy Woman, Dead Horse, and Wild Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

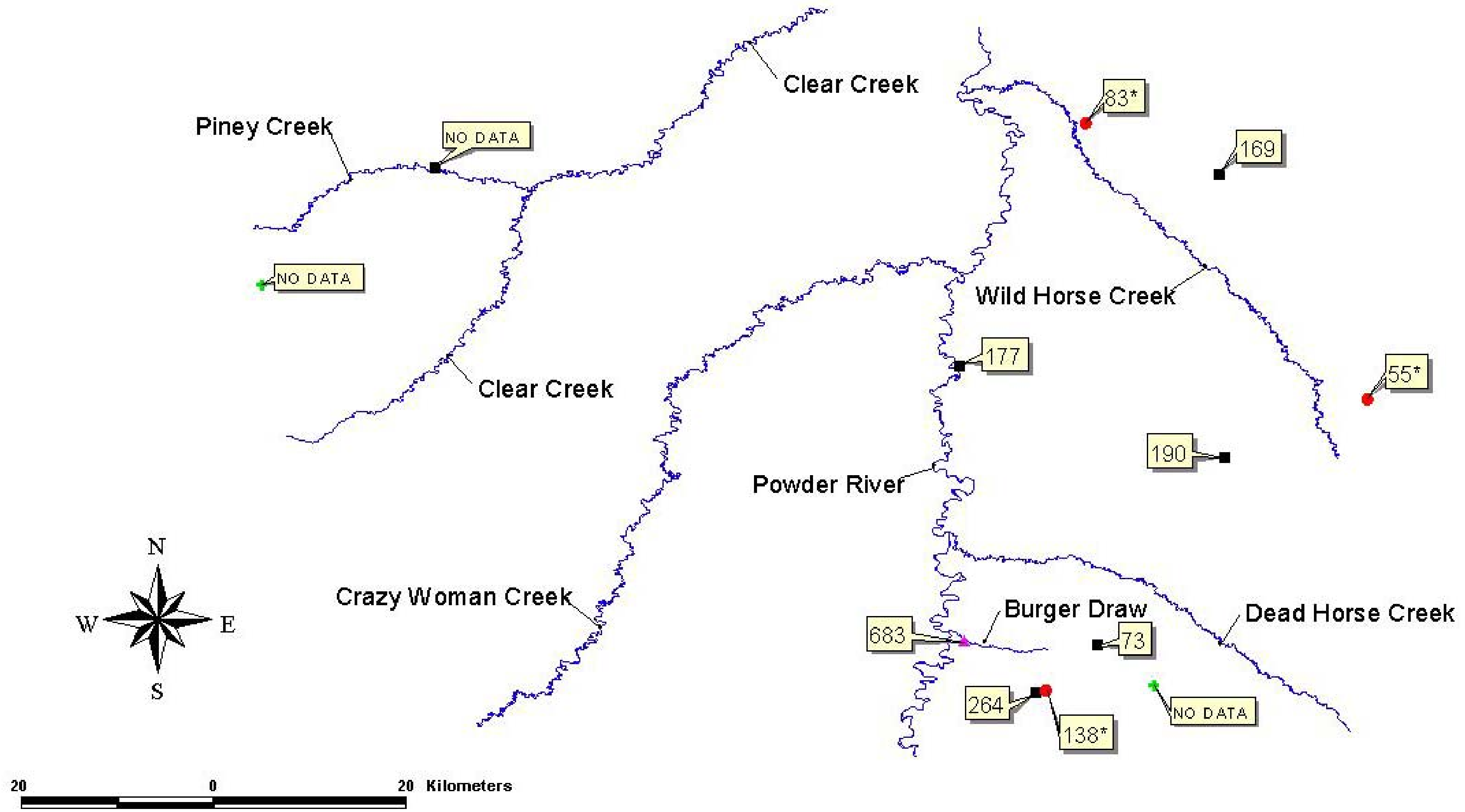

Figure 38. Hardness (mg/L as $CaCO_3$; * indicates values calculated from sum of mEq/L of Ca and Mg) of product water from coalbed methane wells in the southern portion of the Powder River drainage, including Clear, Piney, Crazy Woman, Dead Horse, and Wild Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

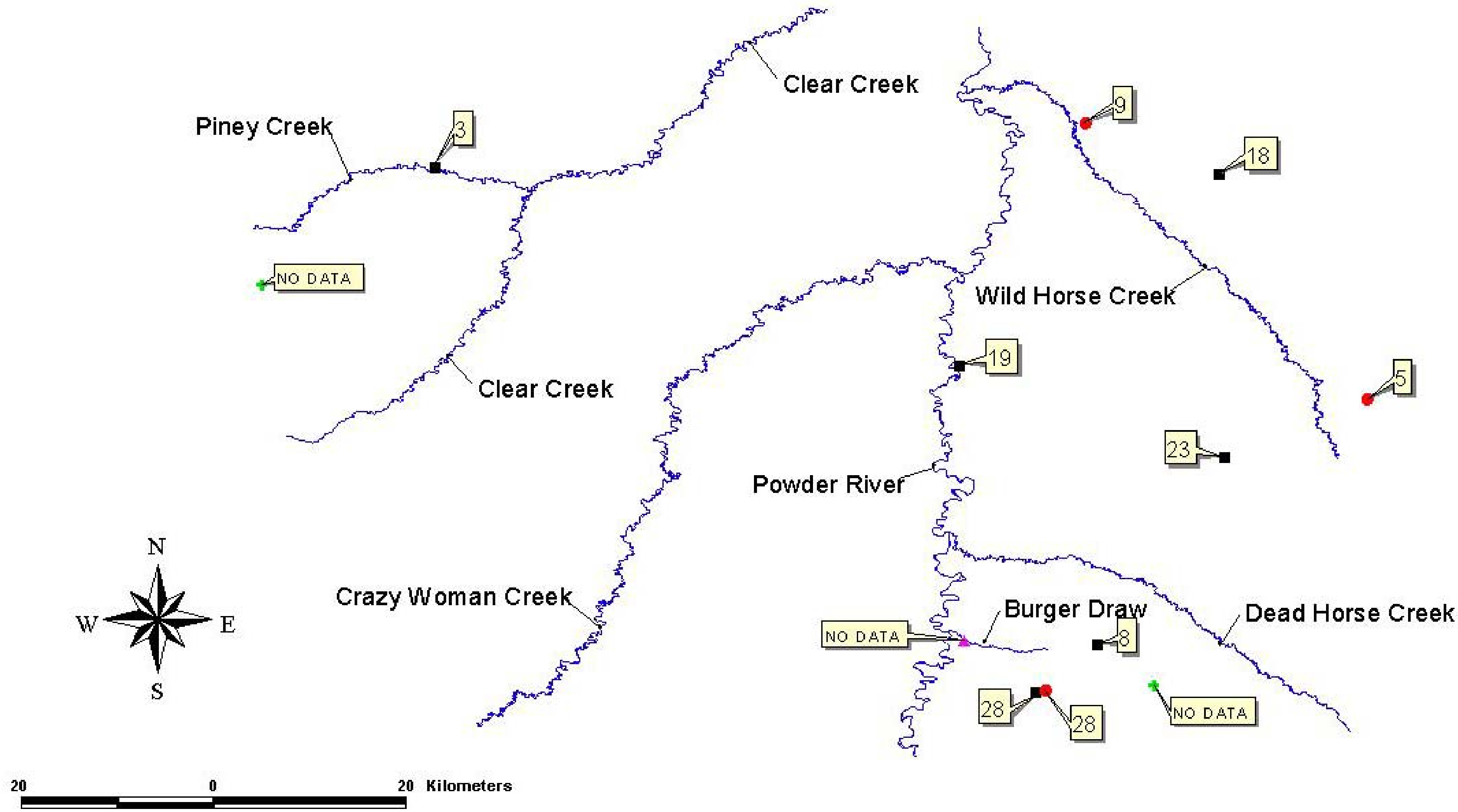

Figure 39. Magnesium concentrations (mg/L) in product water from coalbed methane wells in the southern portion of the Powder River drainage, including Clear, Piney, Crazy Woman, Dead Horse, and Wild Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

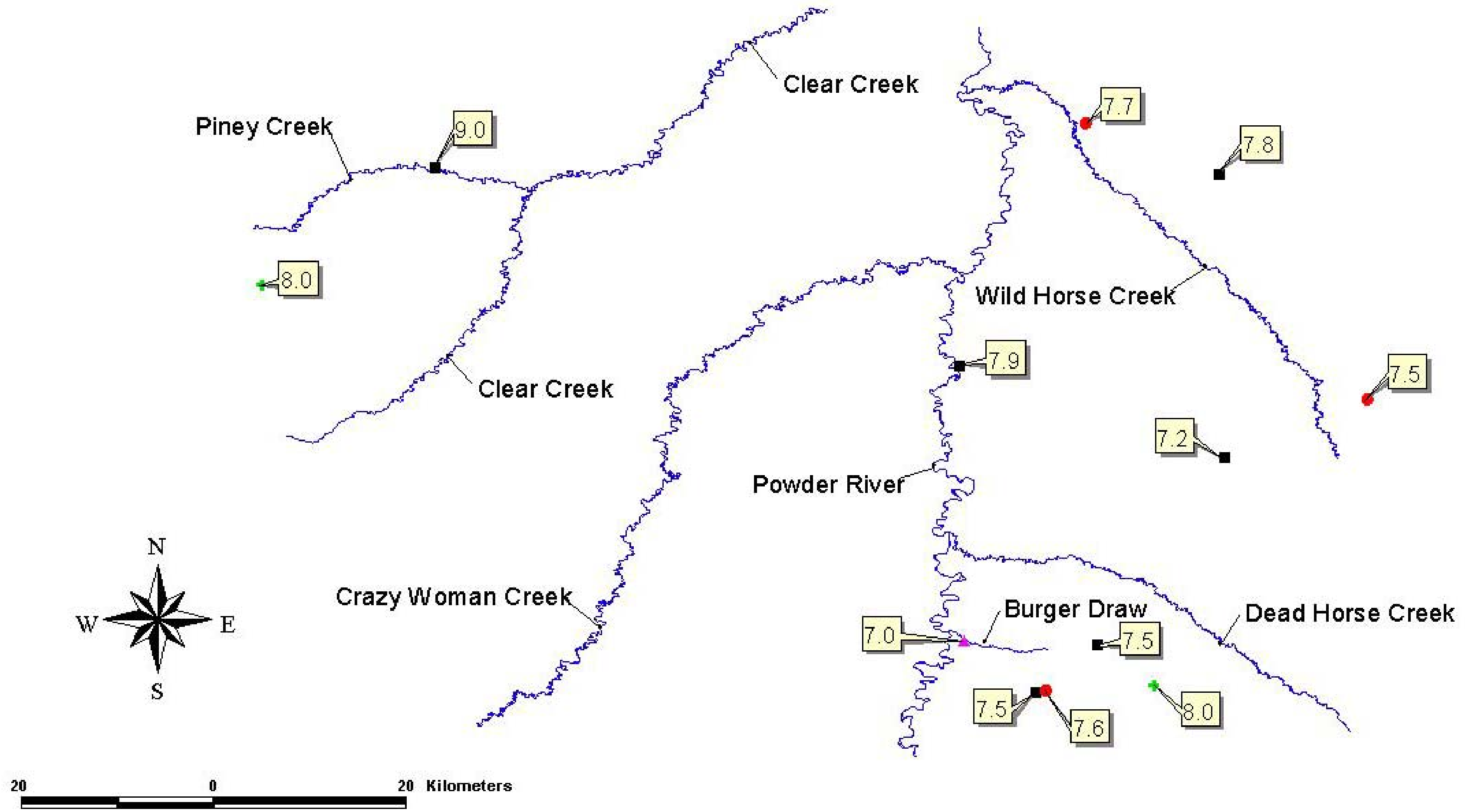

Figure 40. pH (standard units) of product water from coalbed methane wells in the southern portion of the Powder River drainage, including Clear, Piney, Crazy Woman, Dead Horse, and Wild Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

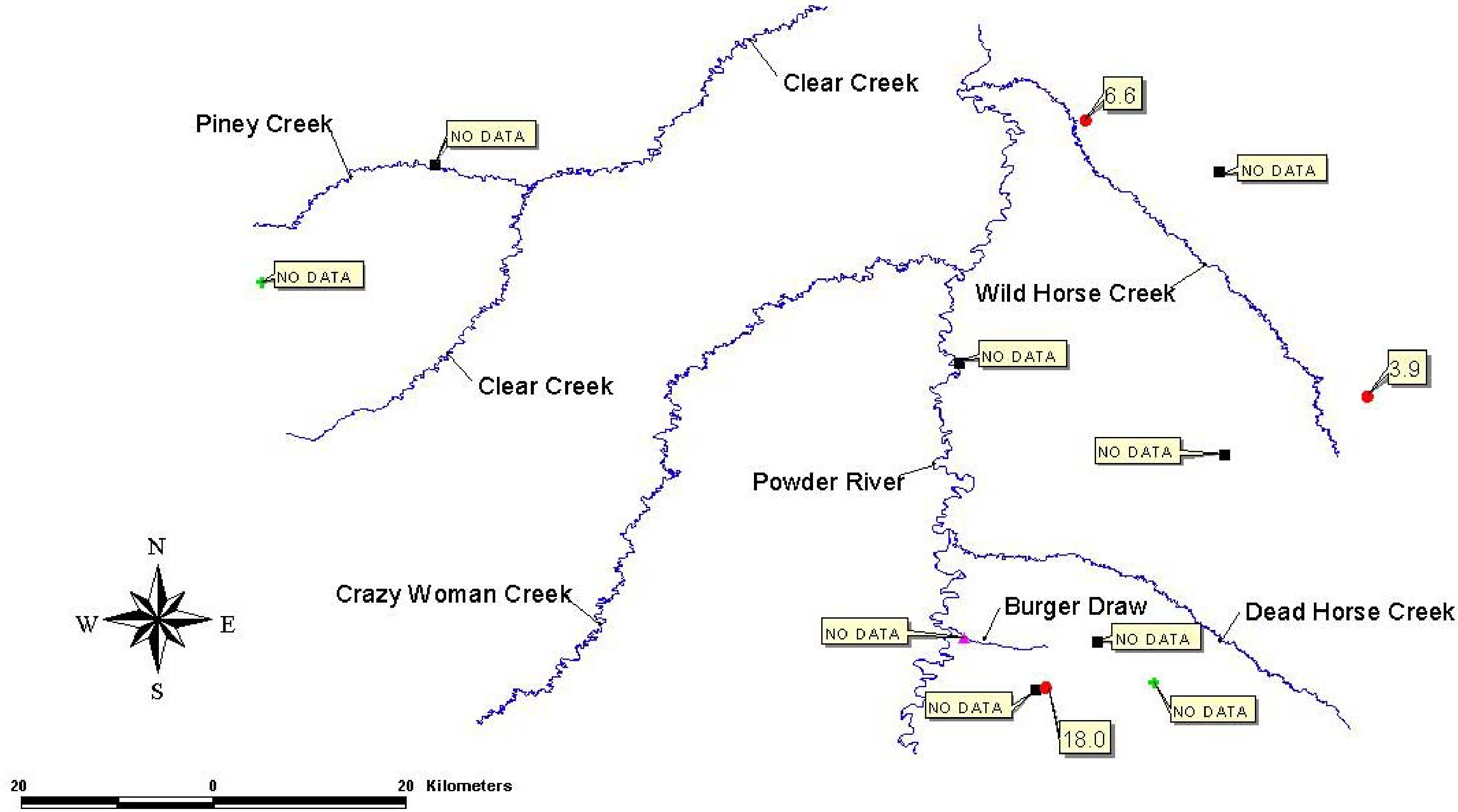

Figure 41. Potassium concentrations (mg/L) in product water from coalbed methane wells in the southern portion of the Powder River drainage, including Clear, Piney, Crazy Woman, Dead Horse, and Wild Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

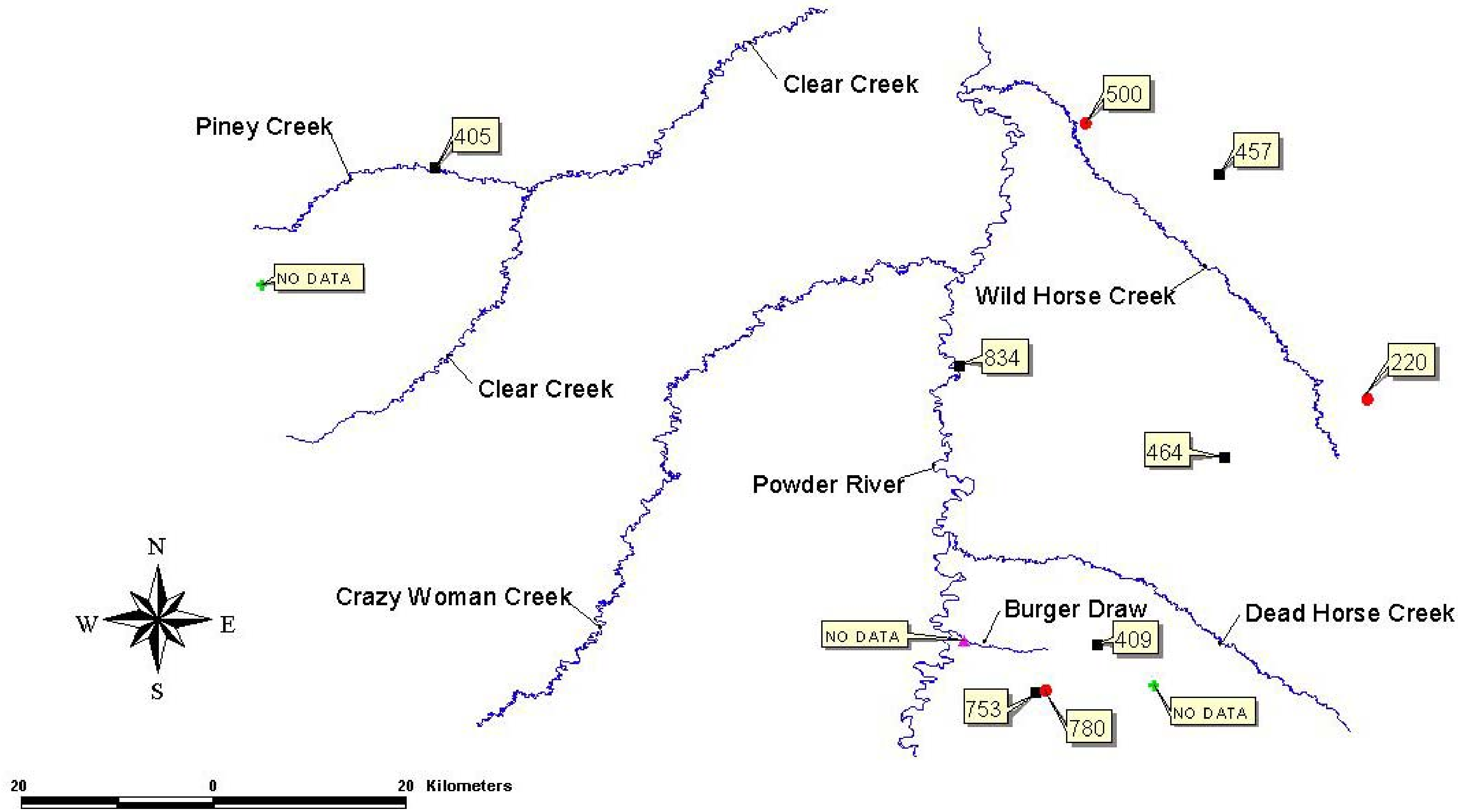

Figure 42. Sodium concentrations (mg/L) in product water from coalbed methane wells in the southern portion of the Powder River drainage, including Clear, Piney, Crazy Woman, Dead Horse, and Wild Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

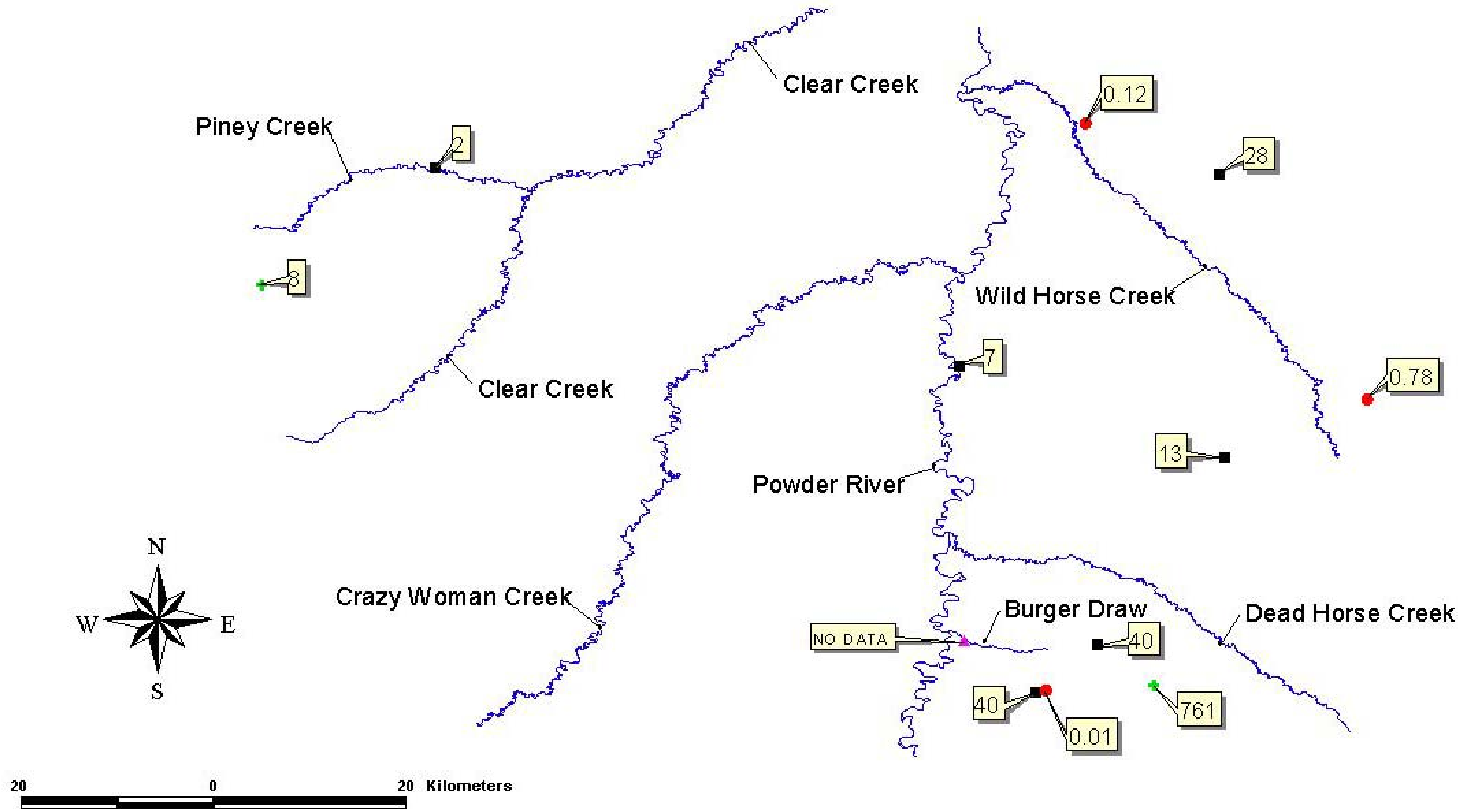

Figure 43. Sulfate concentrations (mg/L) in product water from coalbed methane wells in the southern portion of the Powder River drainage, including Clear, Piney, Crazy Woman, Dead Horse, and Wild Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

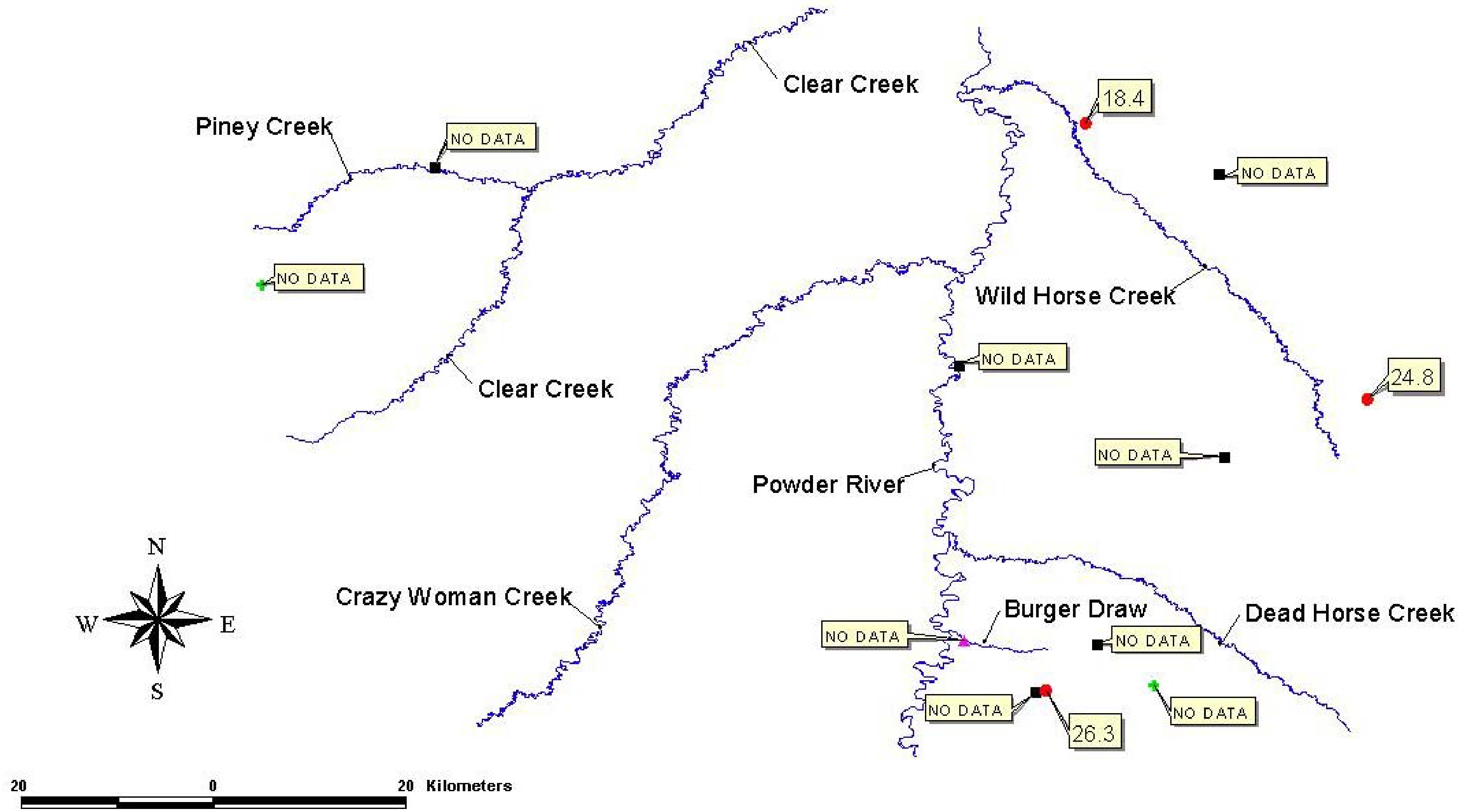

Figure 44. Temperatures (°C) of product water from coalbed methane wells in the southern portion of the Powder River drainage, including Clear, Piney, Crazy Woman, Dead Horse, and Wild Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

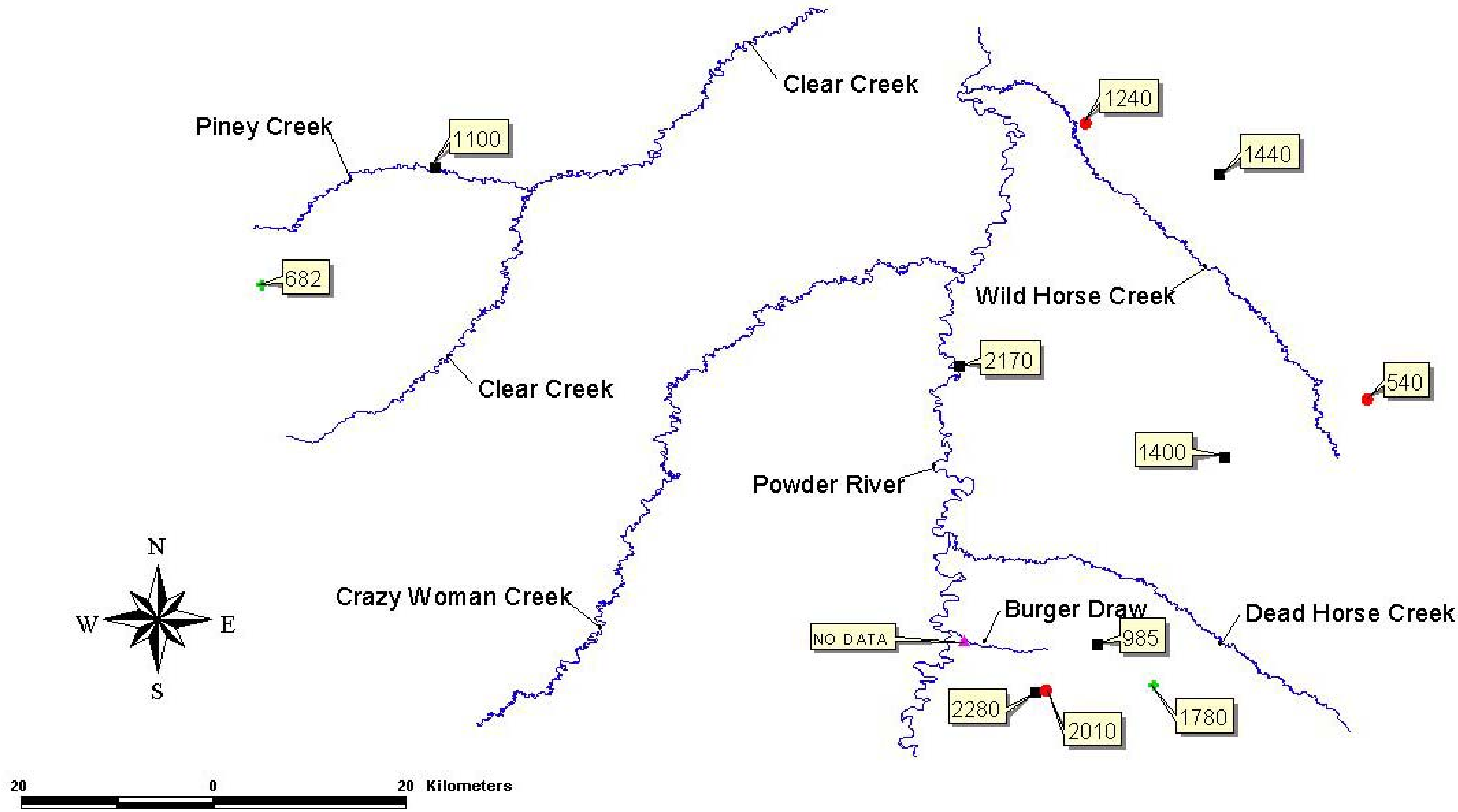

Figure 45. Total dissolved solids concentrations (mg/L) in product water from coalbed methane wells in the southern portion of the Powder River drainage, including Clear, Piney, Crazy Woman, Dead Horse, and Wild Horse Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

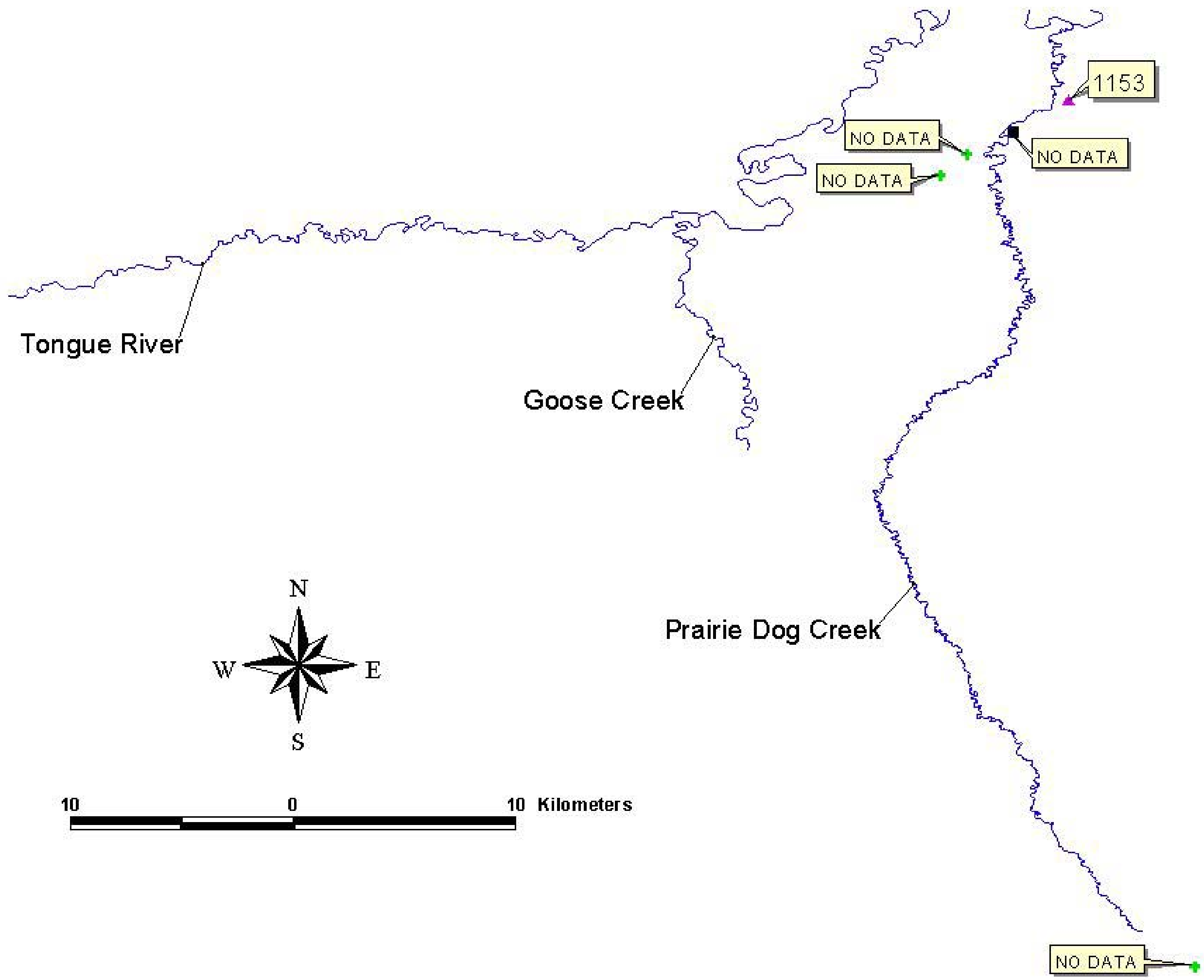

Figure 46. Alkalinity (mg/L as $CaCO_3$) of product water from coalbed methane wells in the Tongue River drainage, including Goose and Prairie Dog Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

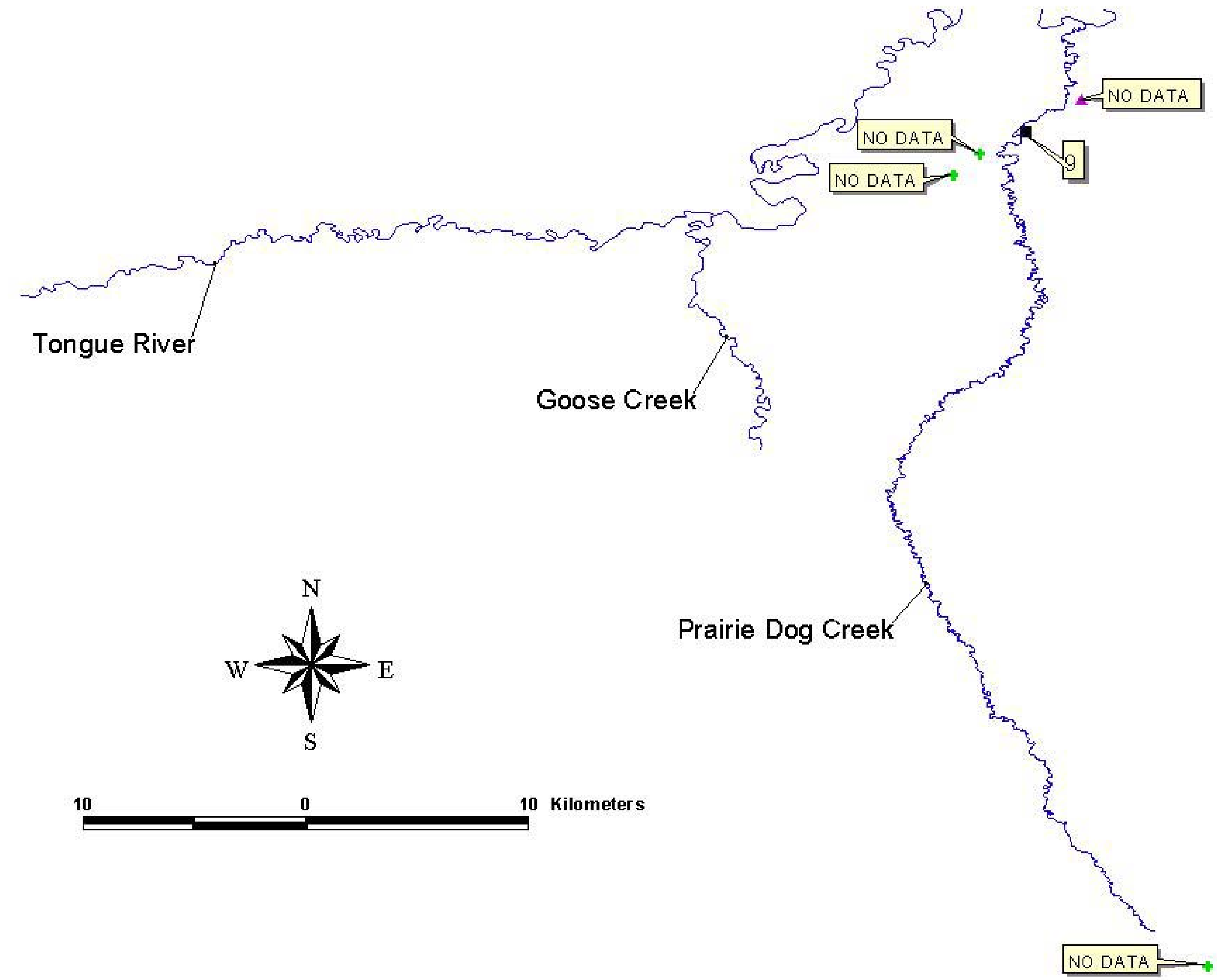

Figure 47. Calcium concentrations (mg/L) in product water from coalbed methane wells in the Tongue River drainage, including Goose and Prairie Dog Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

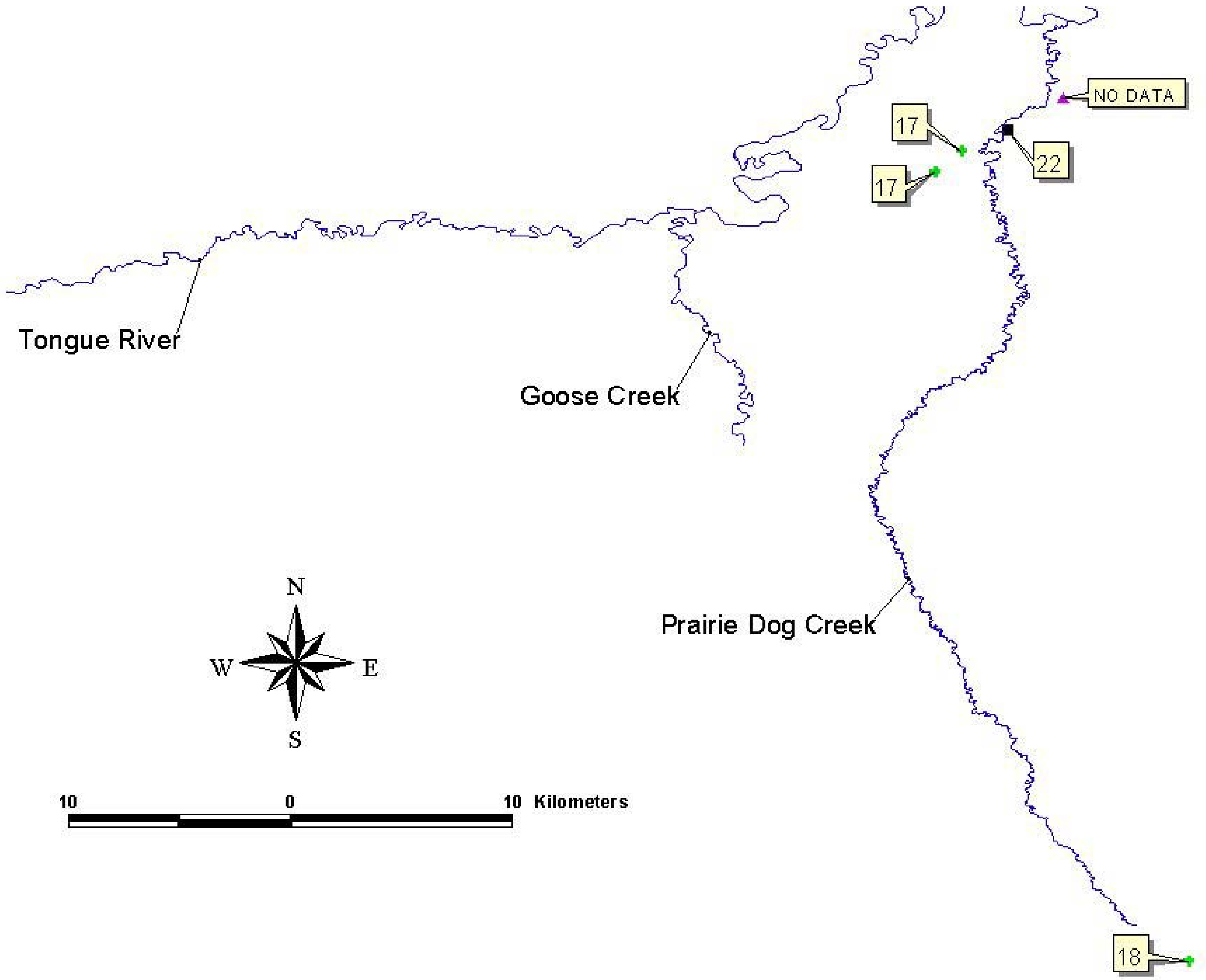

Figure 48. Chloride concentrations (mg/L) in product water from coalbed methane wells in the Tongue River drainage, including Goose and Prairie Dog Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

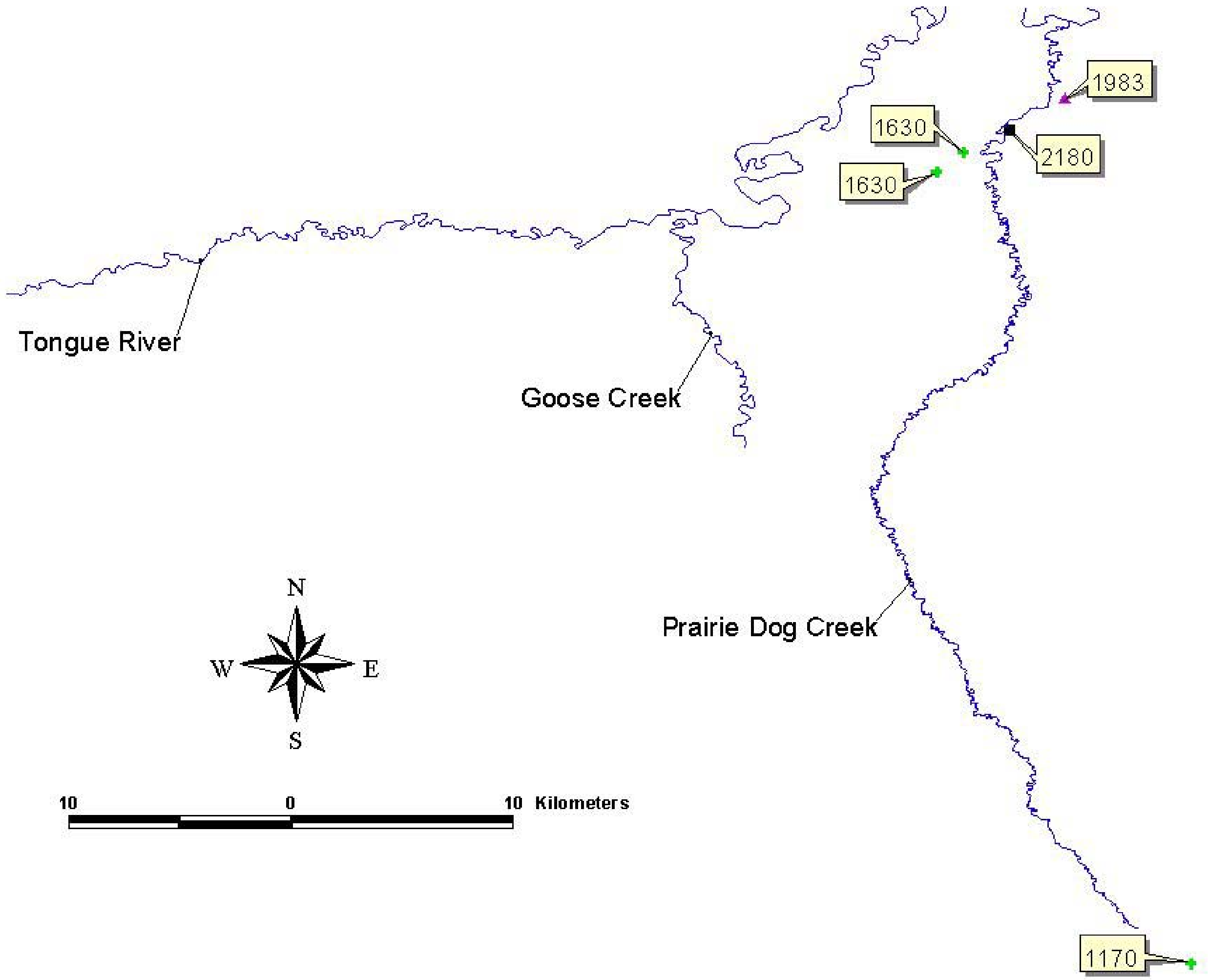

Figure 49. Conductivity (µS/cm) of product water from coalbed methane wells in the Tongue River drainage, including Goose and Prairie Dog Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

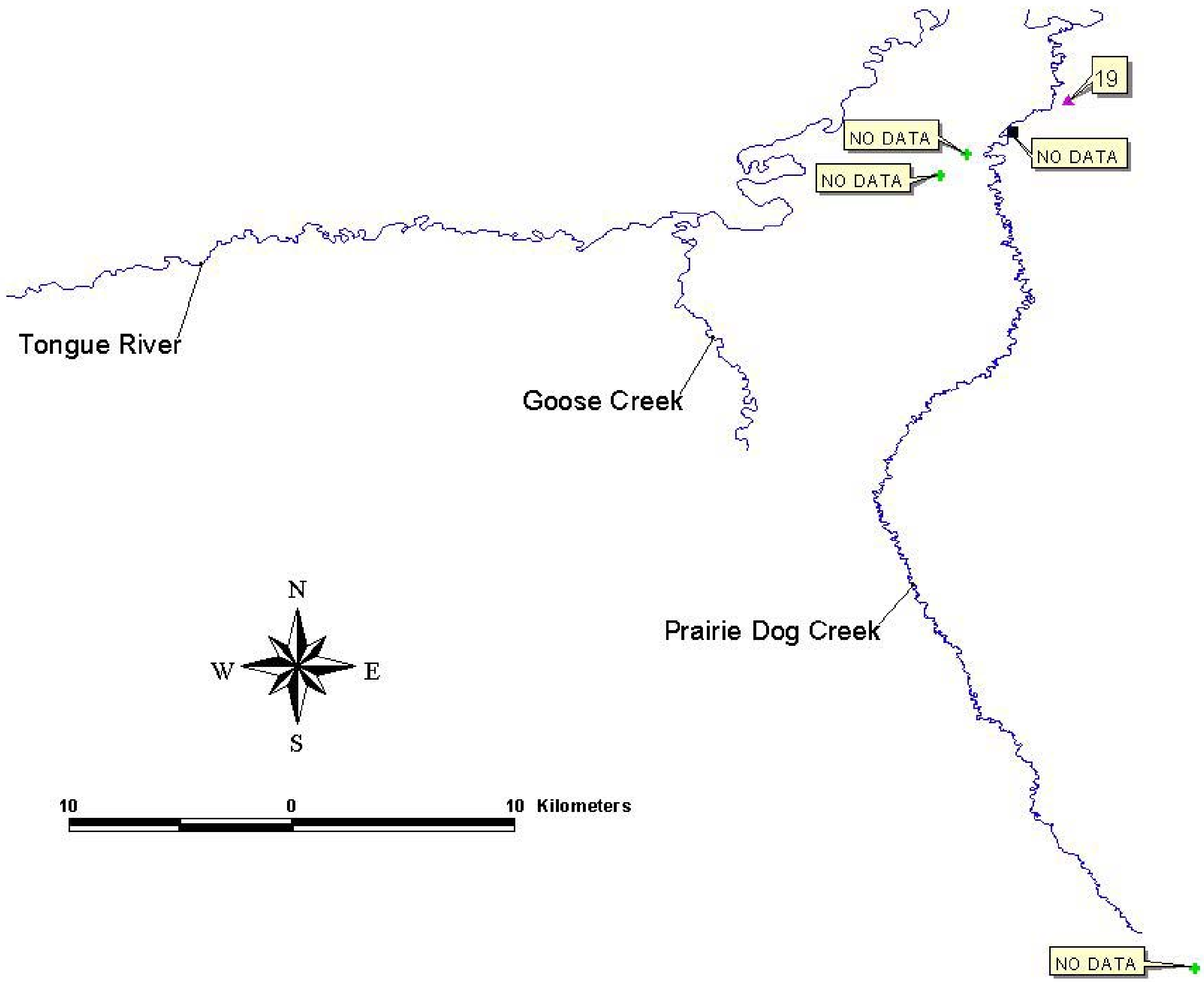

Figure 50. Hardness (mg/L as $CaCO_3$) of product water from coalbed methane wells in the Tongue River drainage, including Goose and Prairie Dog Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

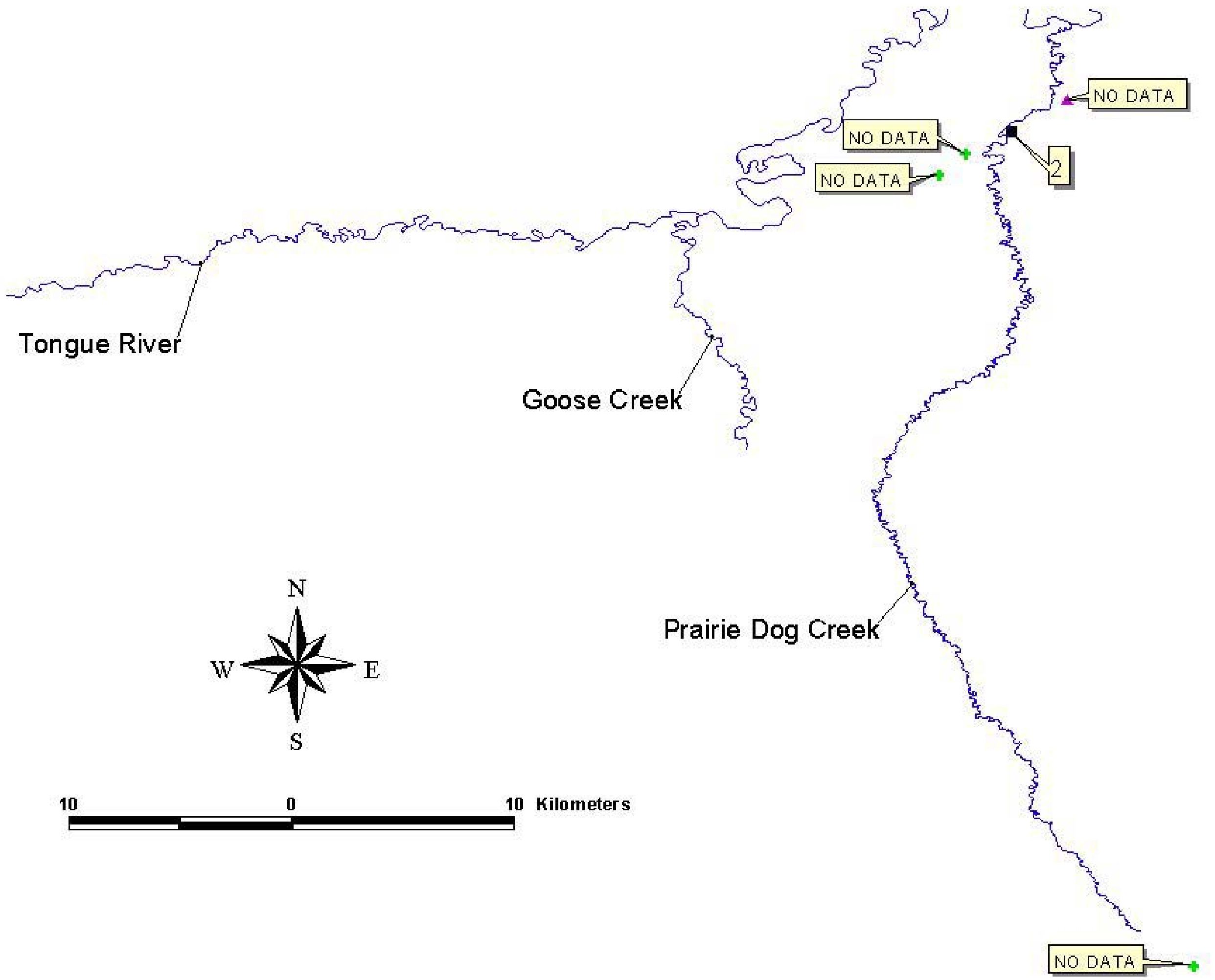

Figure 51. Magnesium concentrations (mg/L) in product water from coalbed methane wells in the Tongue River drainage, including Goose and Prairie Dog Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

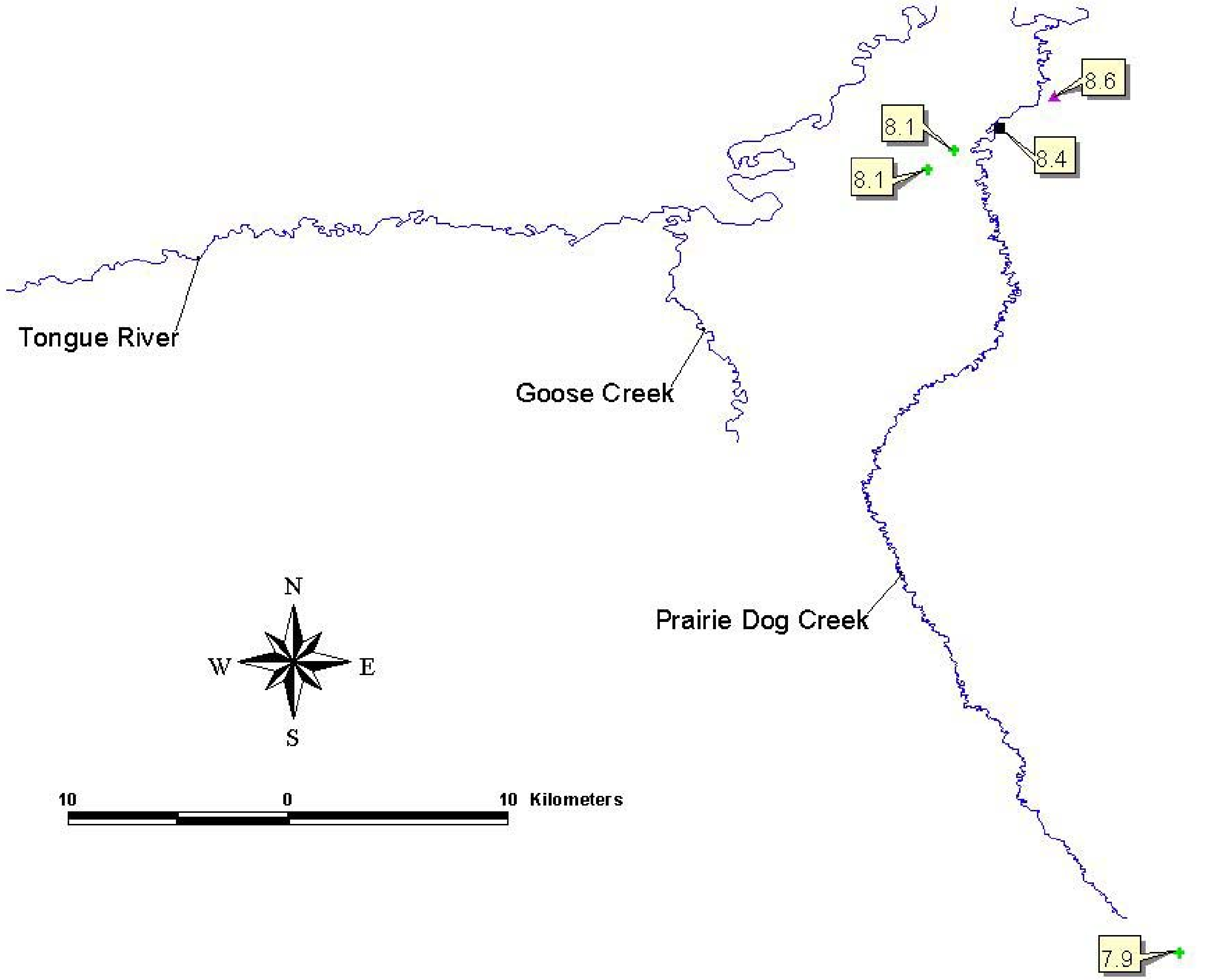

Figure 52. pH (standard units) of product water from coalbed methane wells in the Tongue River drainage, including Goose and Prairie Dog Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

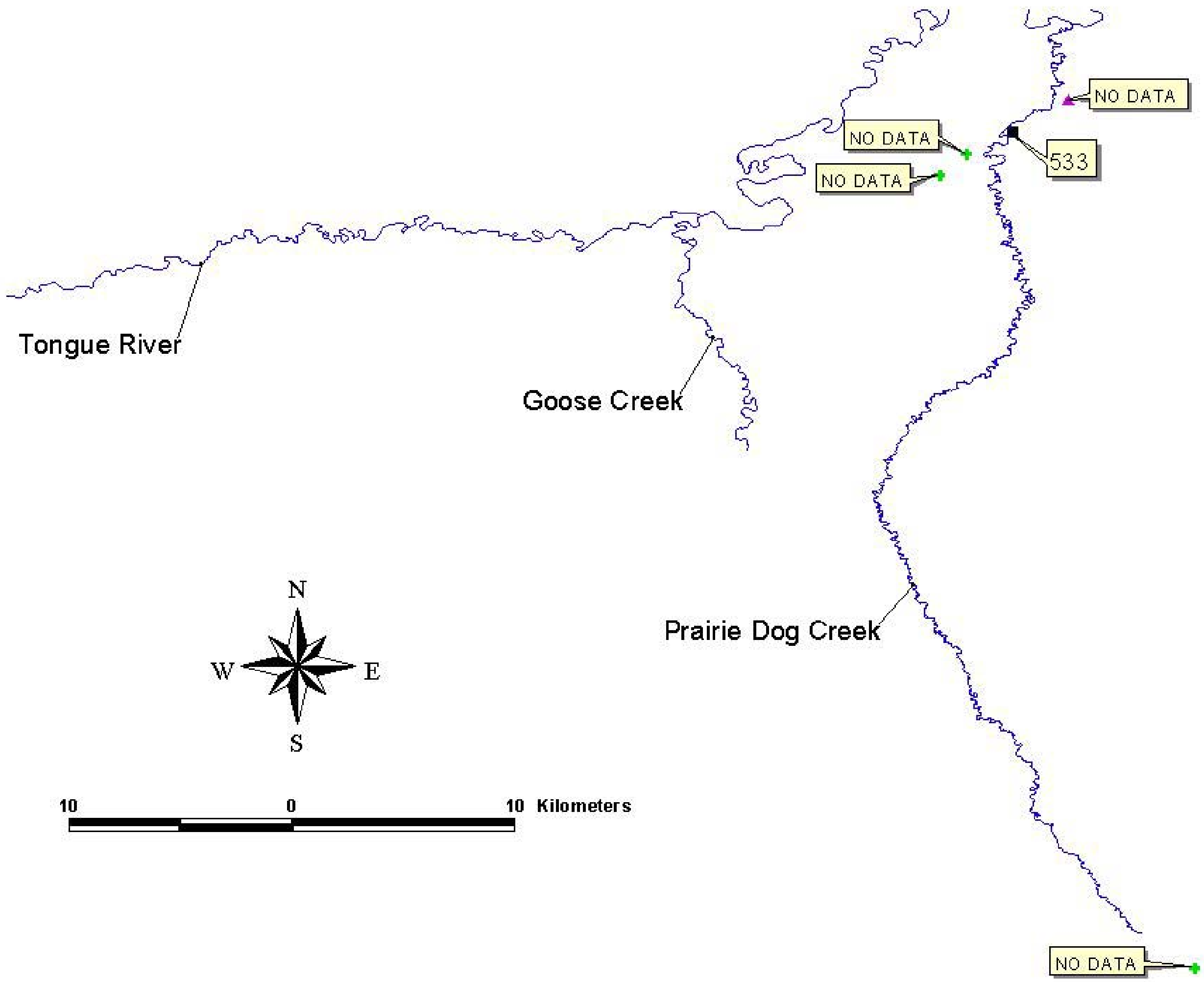

Figure 53. Sodium concentrations (mg/L) in product water from coalbed methane wells in the Tongue River drainage, including Goose and Prairie Dog Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

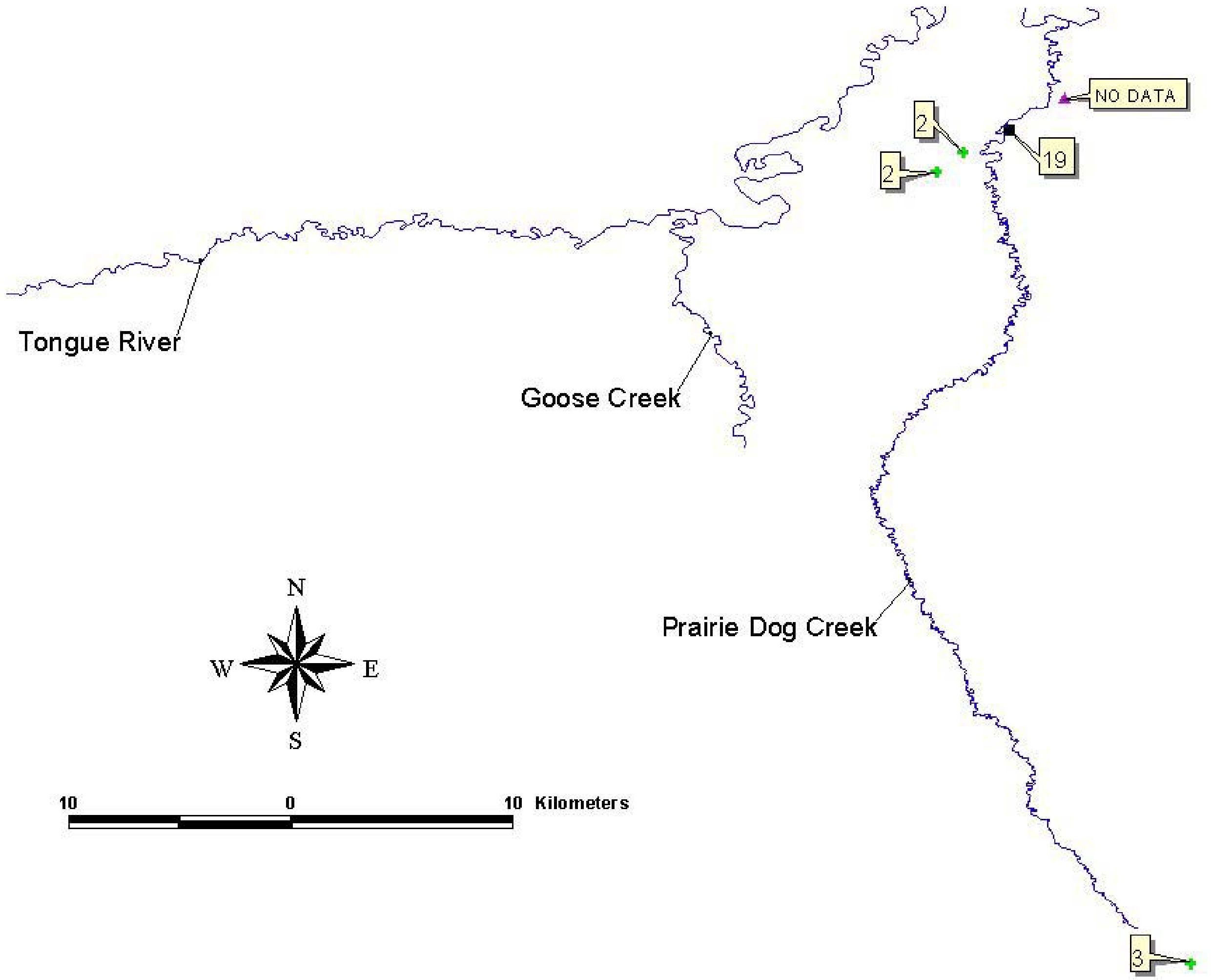

Figure 54. Sulfate concentrations (mg/L) in product water from coalbed methane wells in the Tongue River drainage, including Goose and Prairie Dog Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

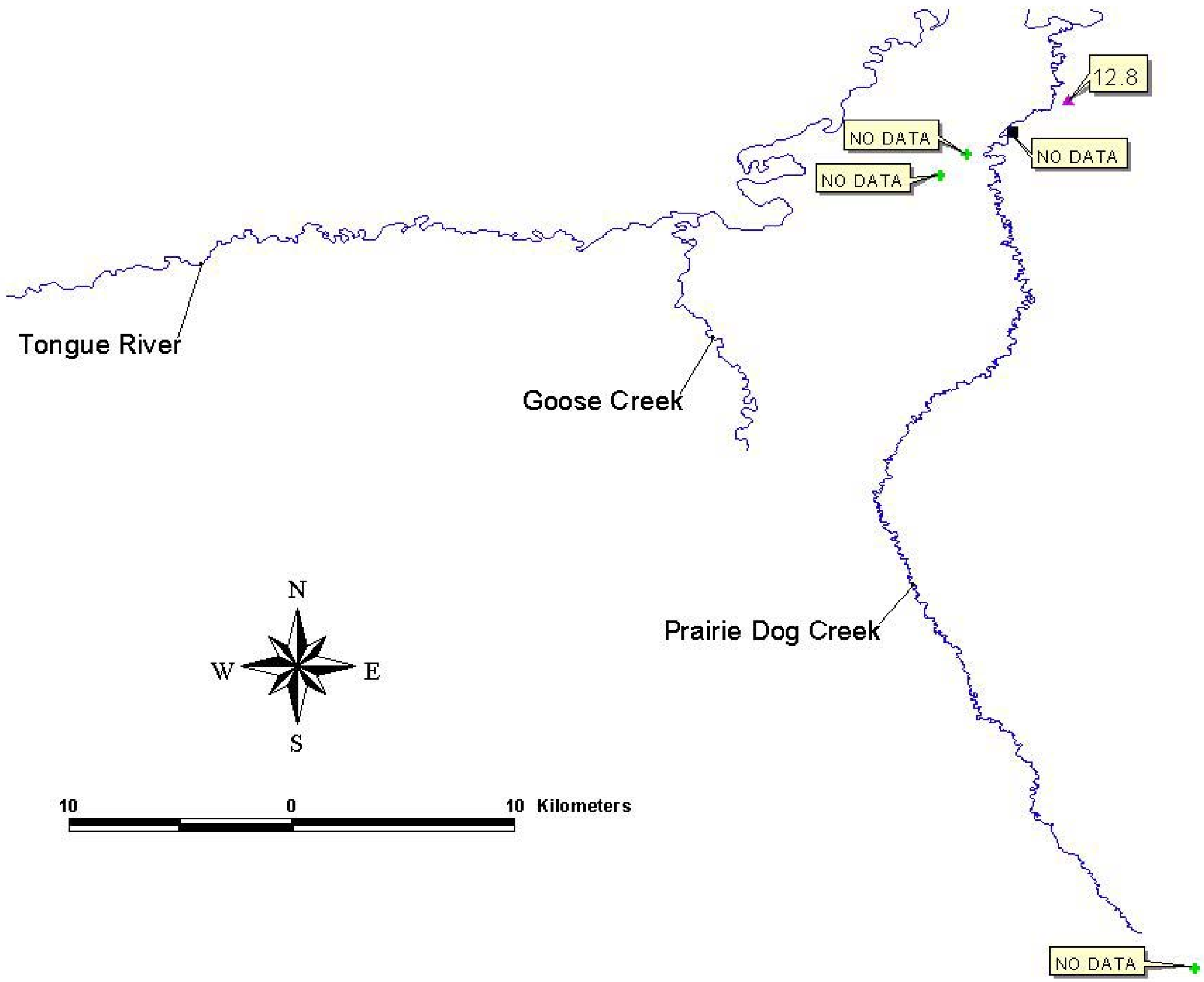

Figure 55. Temperatures (°C) of product water from coalbed methane wells in the Tongue River drainage, including Goose and Prairie Dog Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

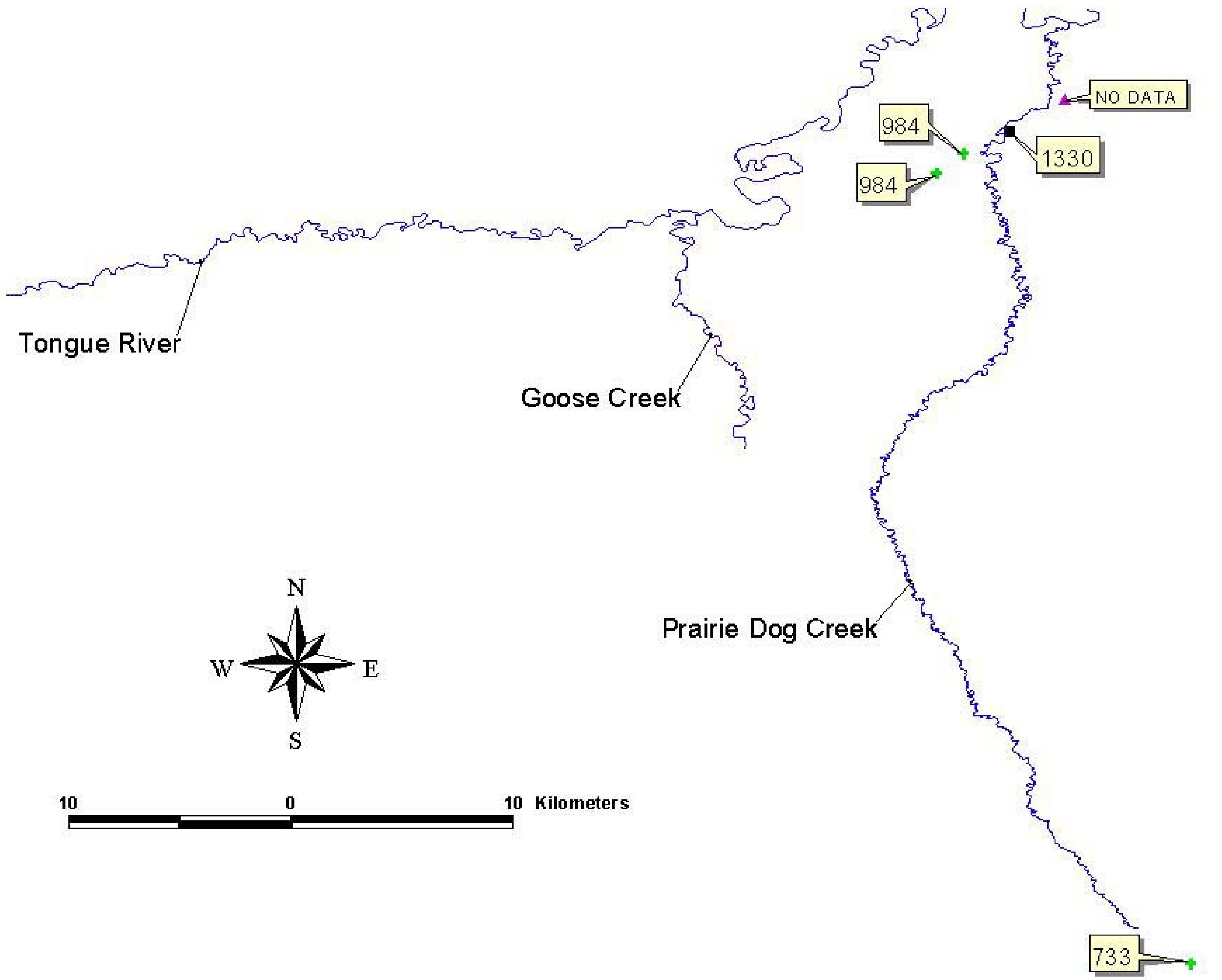

Figure 56. Total dissolved solids concentrations (mg/L) in product water from coalbed methane wells in the Tongue River drainage, including Goose and Prairie Dog Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

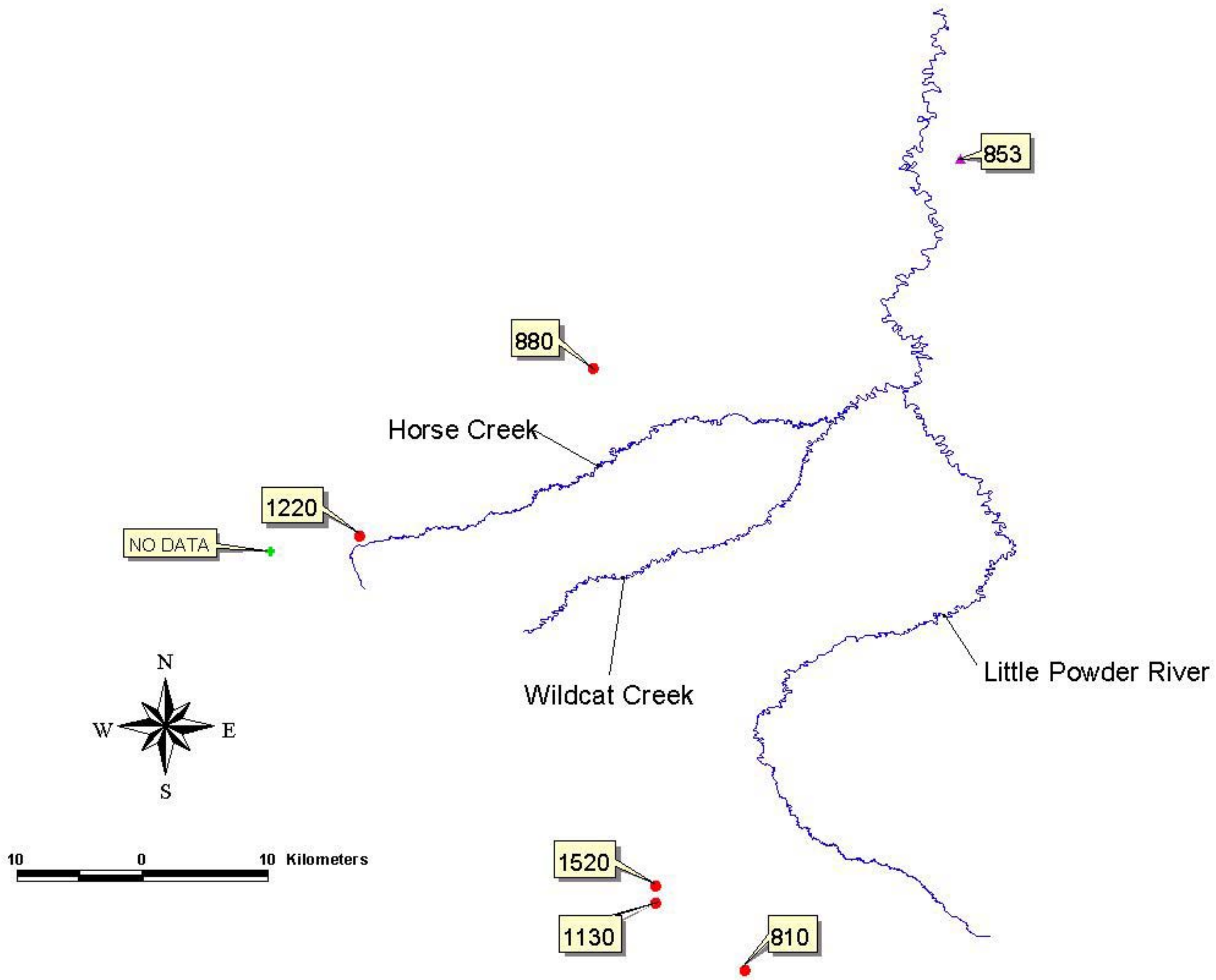

Figure 57. Alkalinity (mg/L as $CaCO_3$) of product water from coalbed methane wells in the Little Powder River drainage, including Horse and Wildcat Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

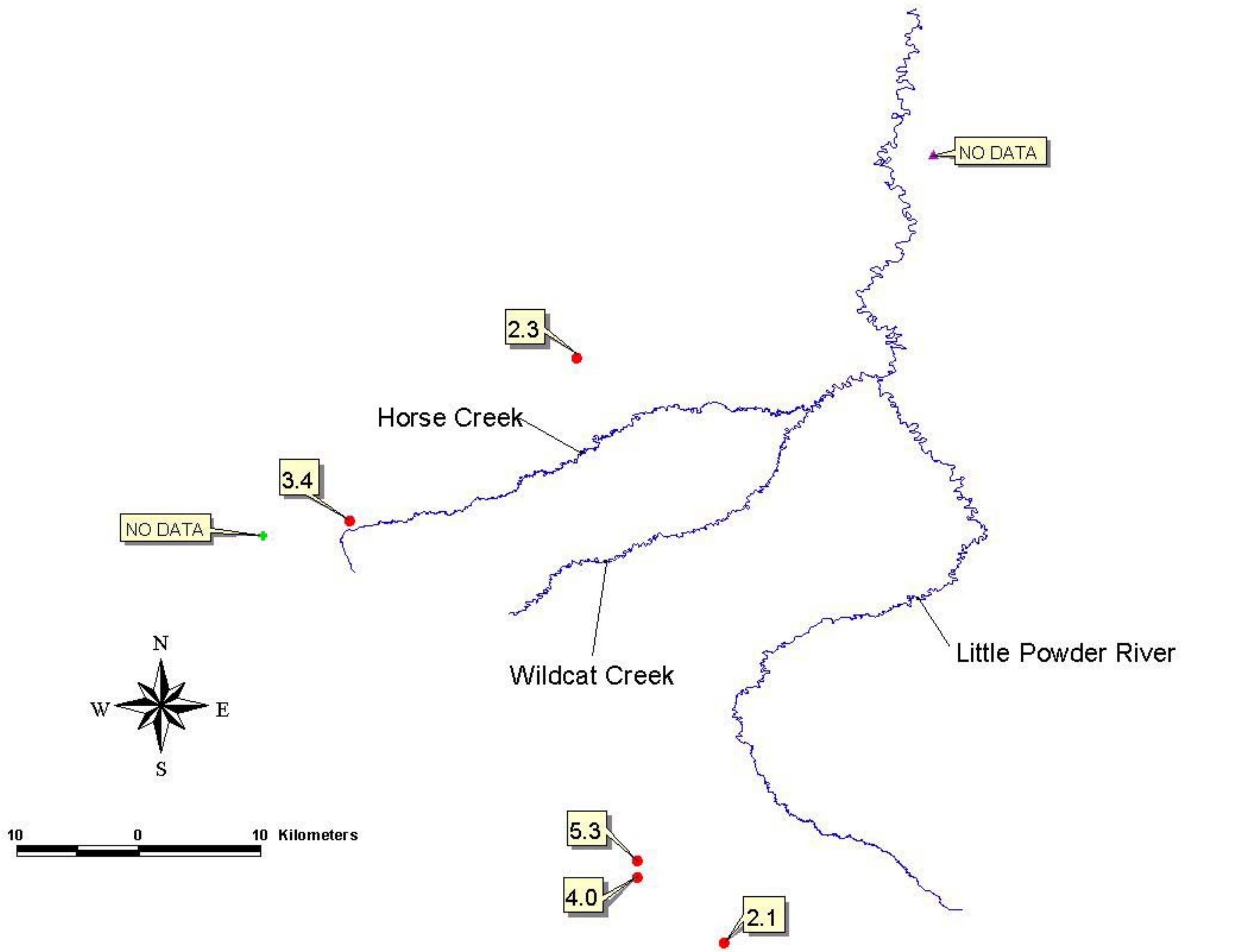

Figure 58. Ammonia concentrations (mg NH_4^+/L) in product water from coalbed methane wells in the Little Powder River drainage, including Horse and Wildcat Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

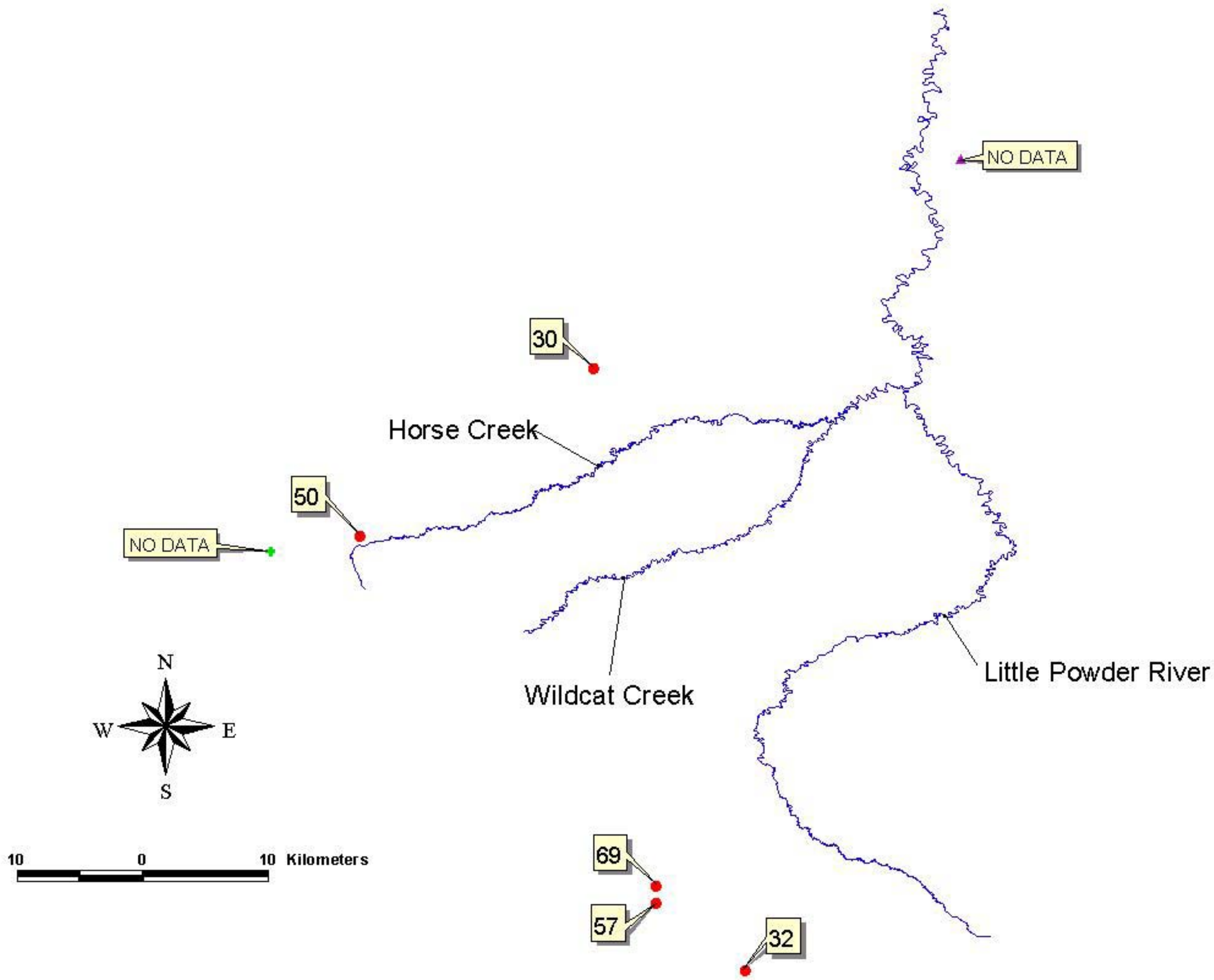

Figure 59. Calcium concentrations (mg/L) in product water from coalbed methane wells in the Little Powder River drainage, including Horse and Wildcat Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

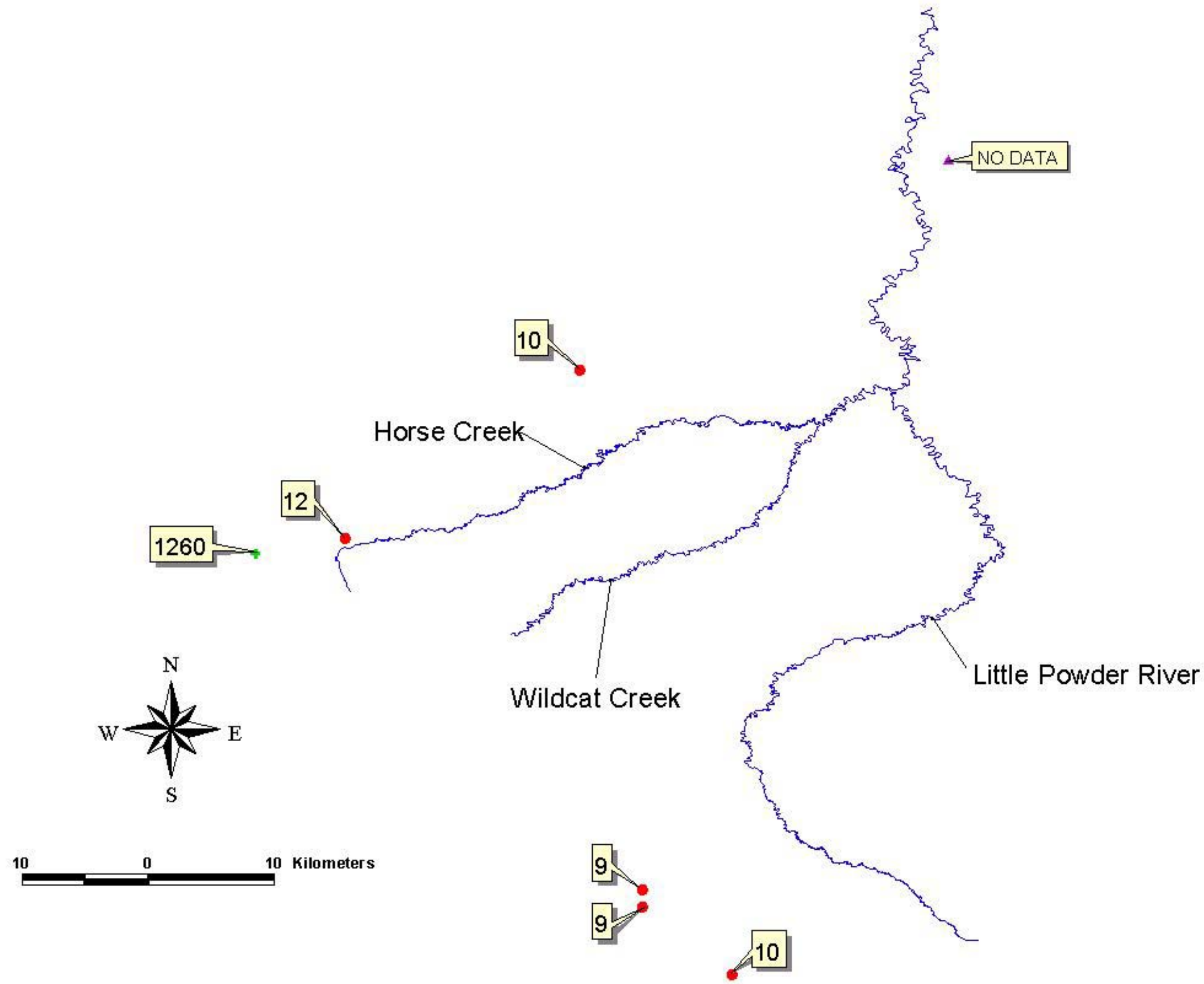

Figure 60. Chloride concentrations (mg/L) in product water from coalbed methane wells in the Little Powder River drainage, including Horse and Wildcat Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

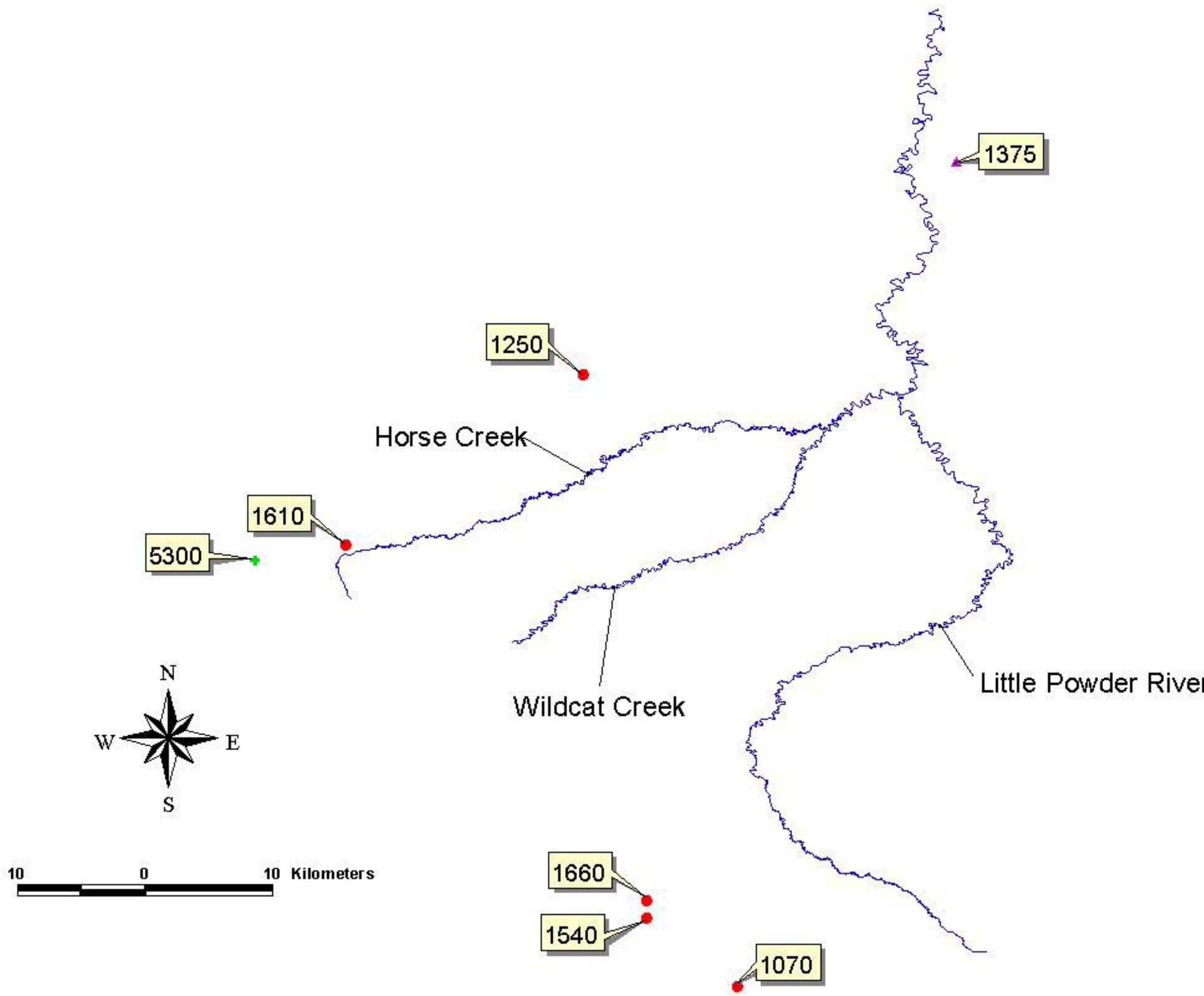

Figure 61. Conductivity (μS/cm) of product water from coalbed methane wells in the Little Powder River drainage, including Horse and Wildcat Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

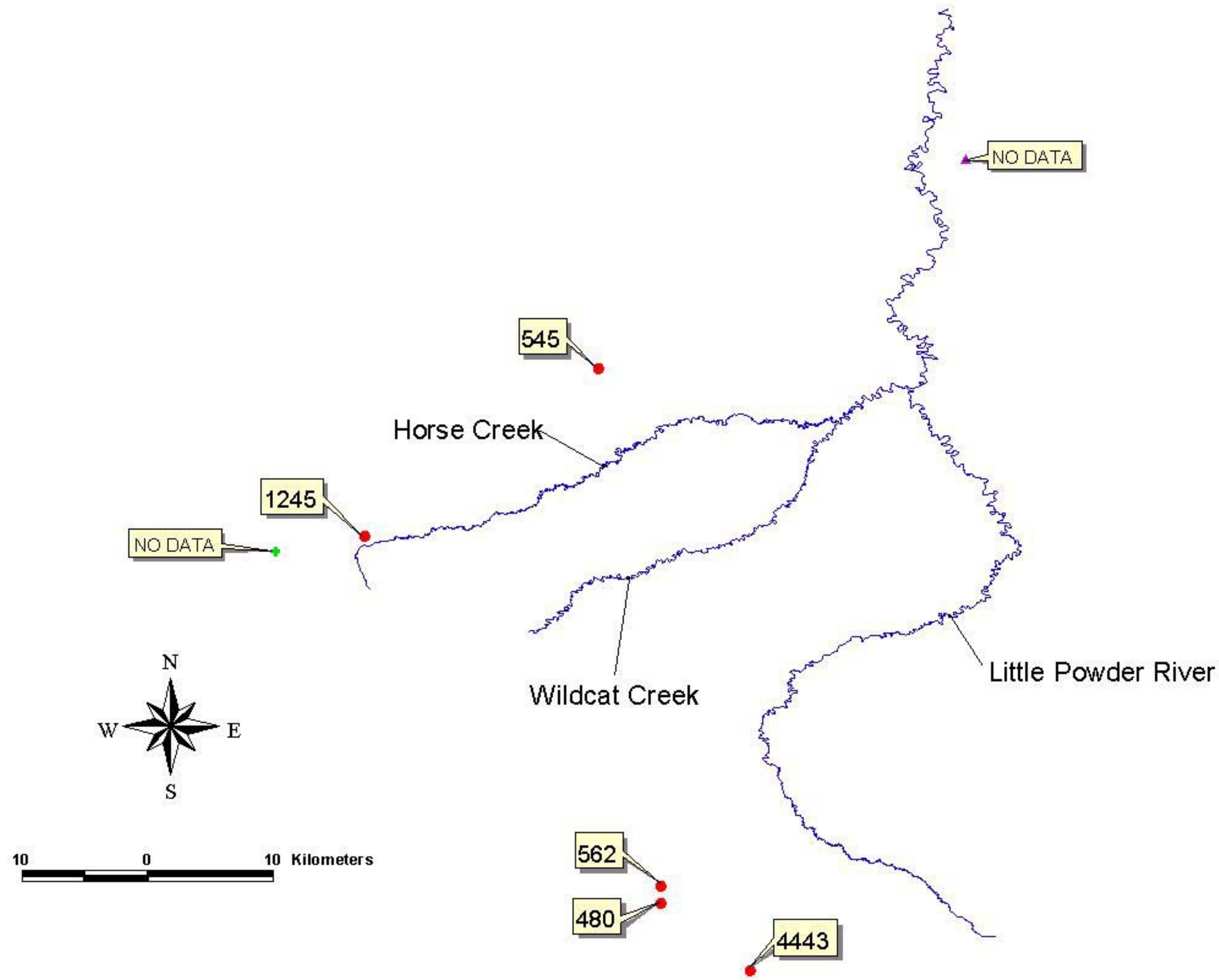

Figure 62. Depth (ft) of coalbed methane wells in the Little Powder River drainage, including Horse and Wildcat Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

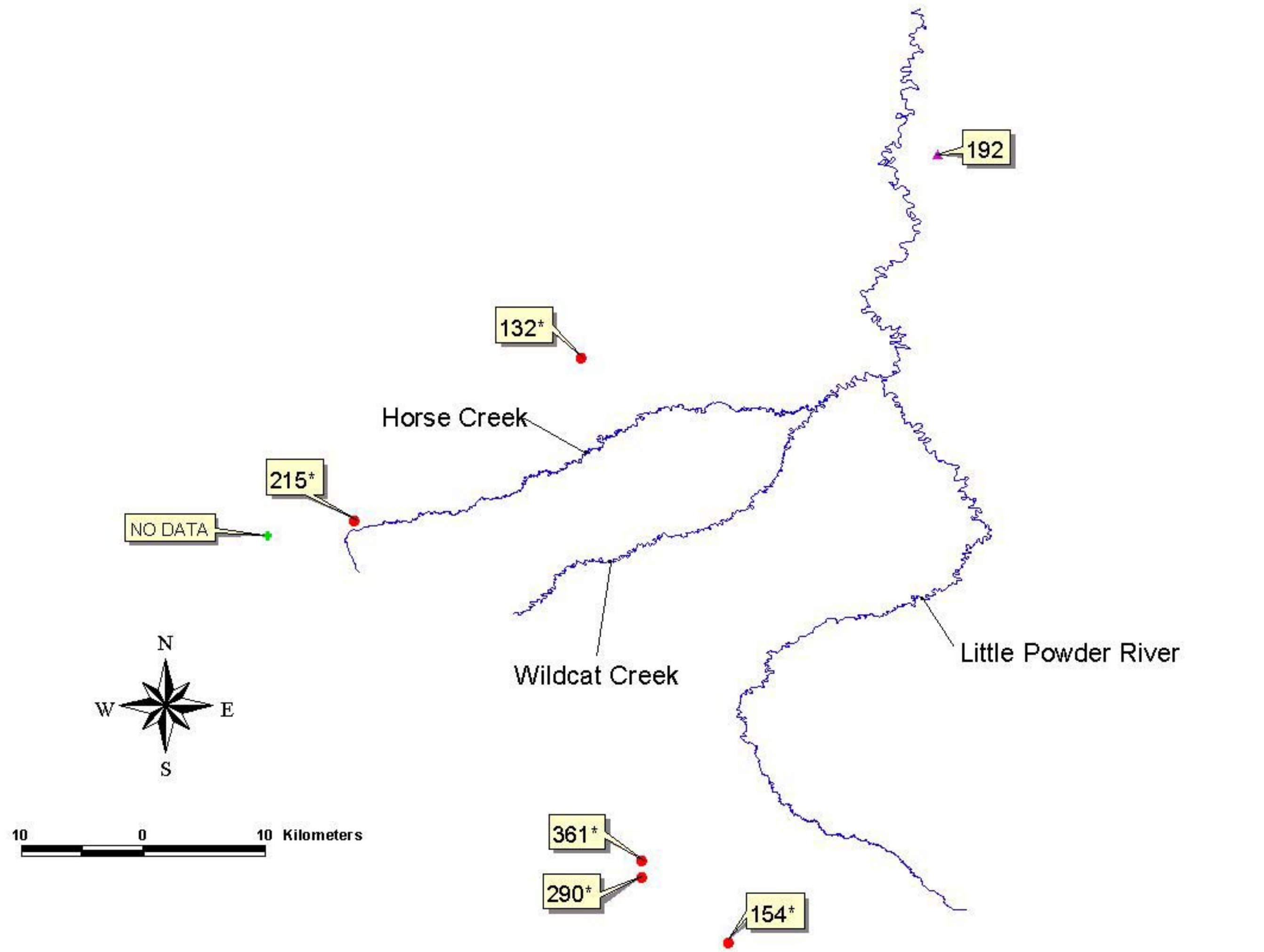

Figure 63. Hardness (mg/L as $CaCO_3$; * indicates values calculated from sum of mEq/L of Ca and Mg) of product water from coalbed methane wells in the Little Powder River drainage, including Horse and Wildcat Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

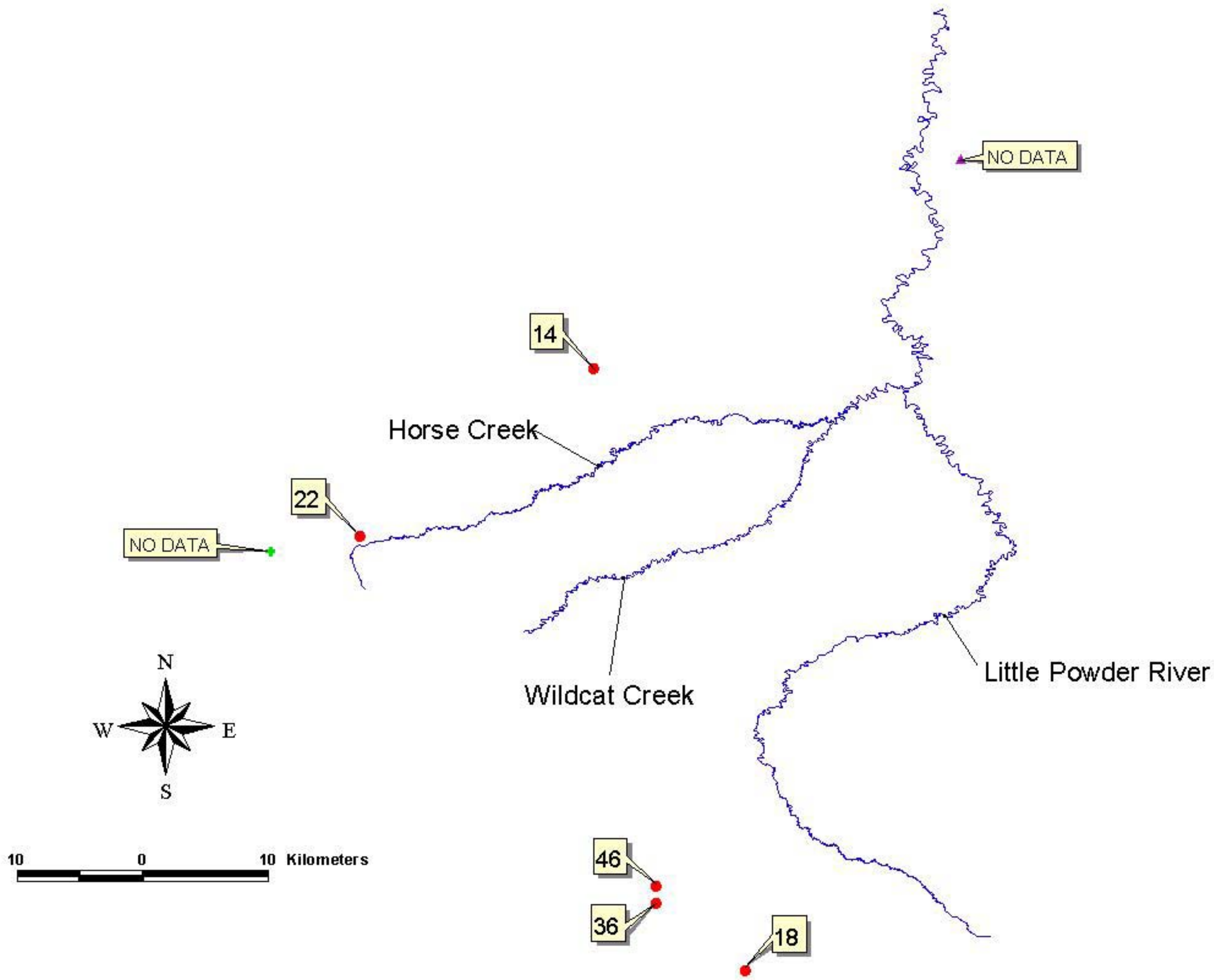

Figure 64. Magnesium concentrations (mg/L) in product water from coalbed methane wells in the Little Powder River drainage, including Horse and Wildcat Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

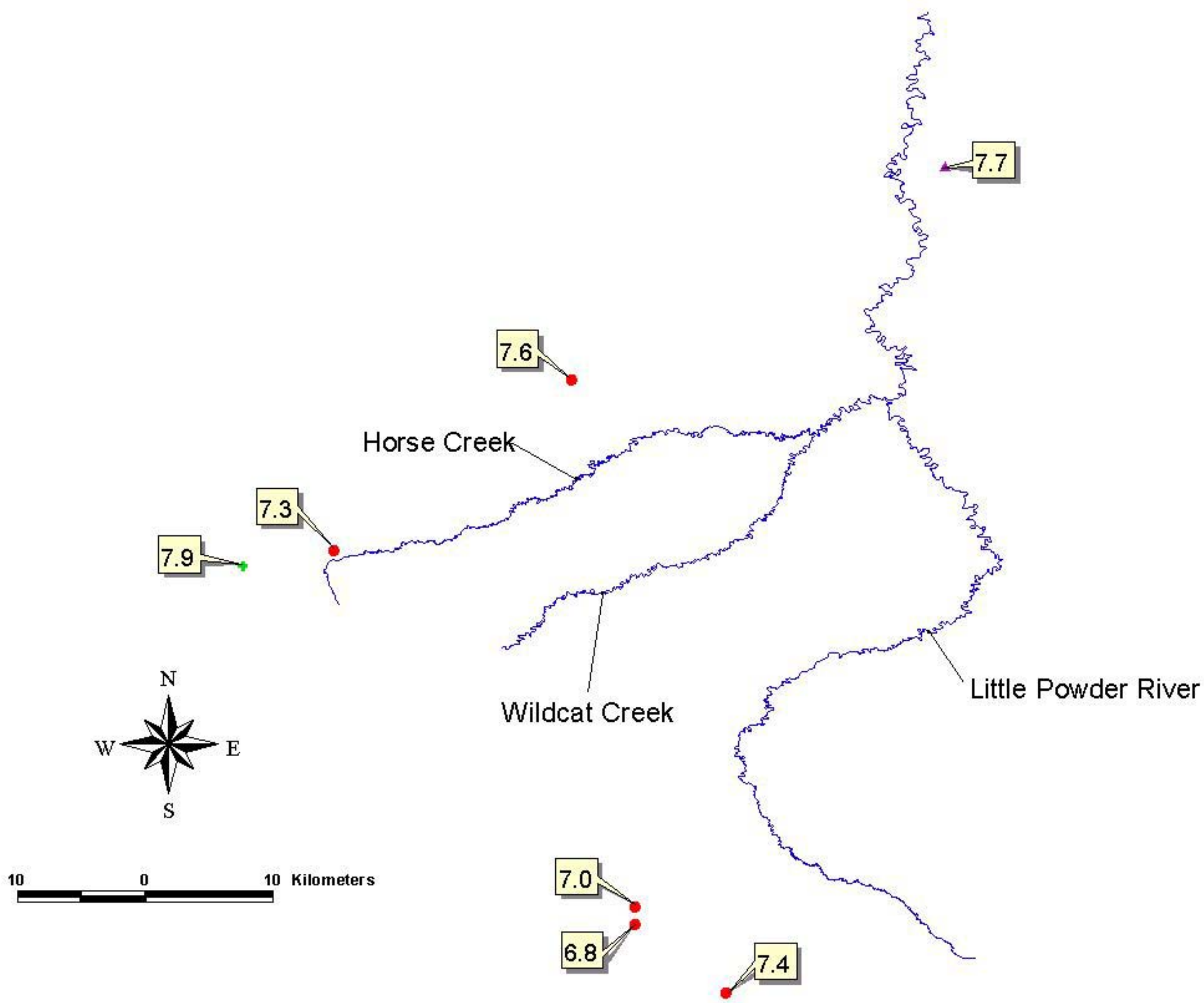

Figure 65. pH (standard units) of product water from coalbed methane wells in the Little Powder River drainage, including Horse and Wildcat Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

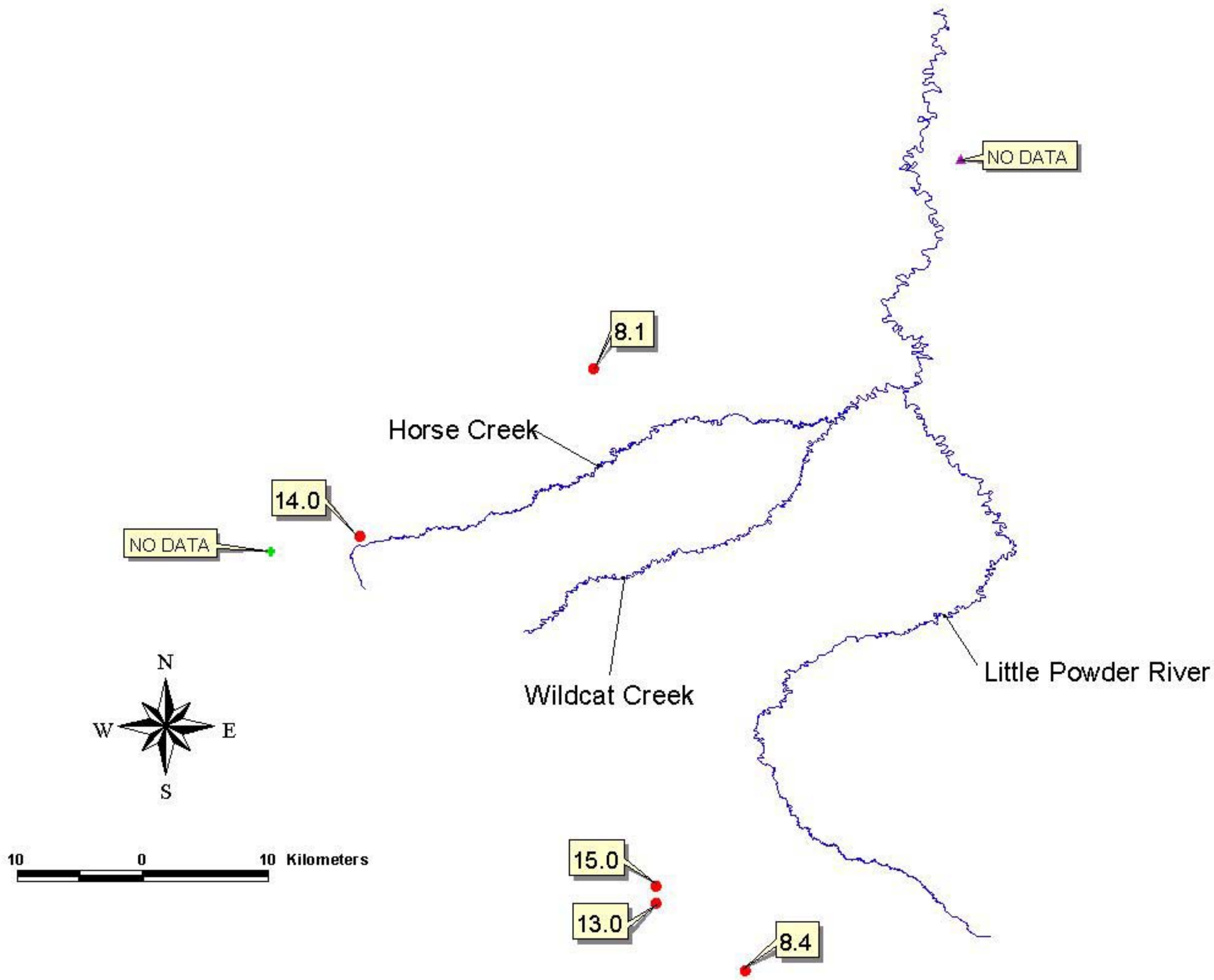

Figure 66. Potassium concentrations (mg/L) in product water from coalbed methane wells in the Little Powder River drainage, including Horse and Wildcat Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

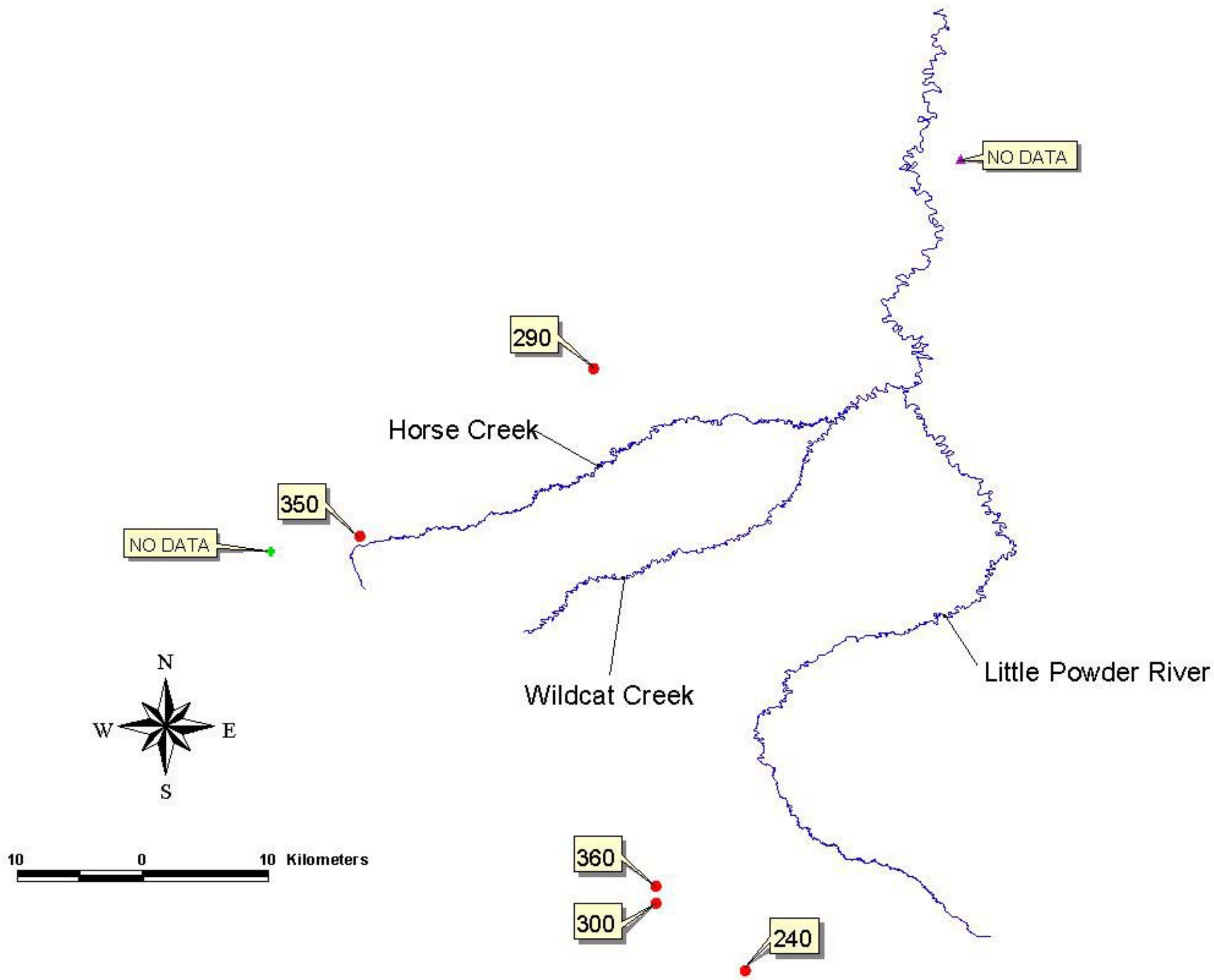

Figure 67. Sodium concentrations (mg/L) in product water from coalbed methane wells in the Little Powder River drainage, including Horse and Wildcat Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

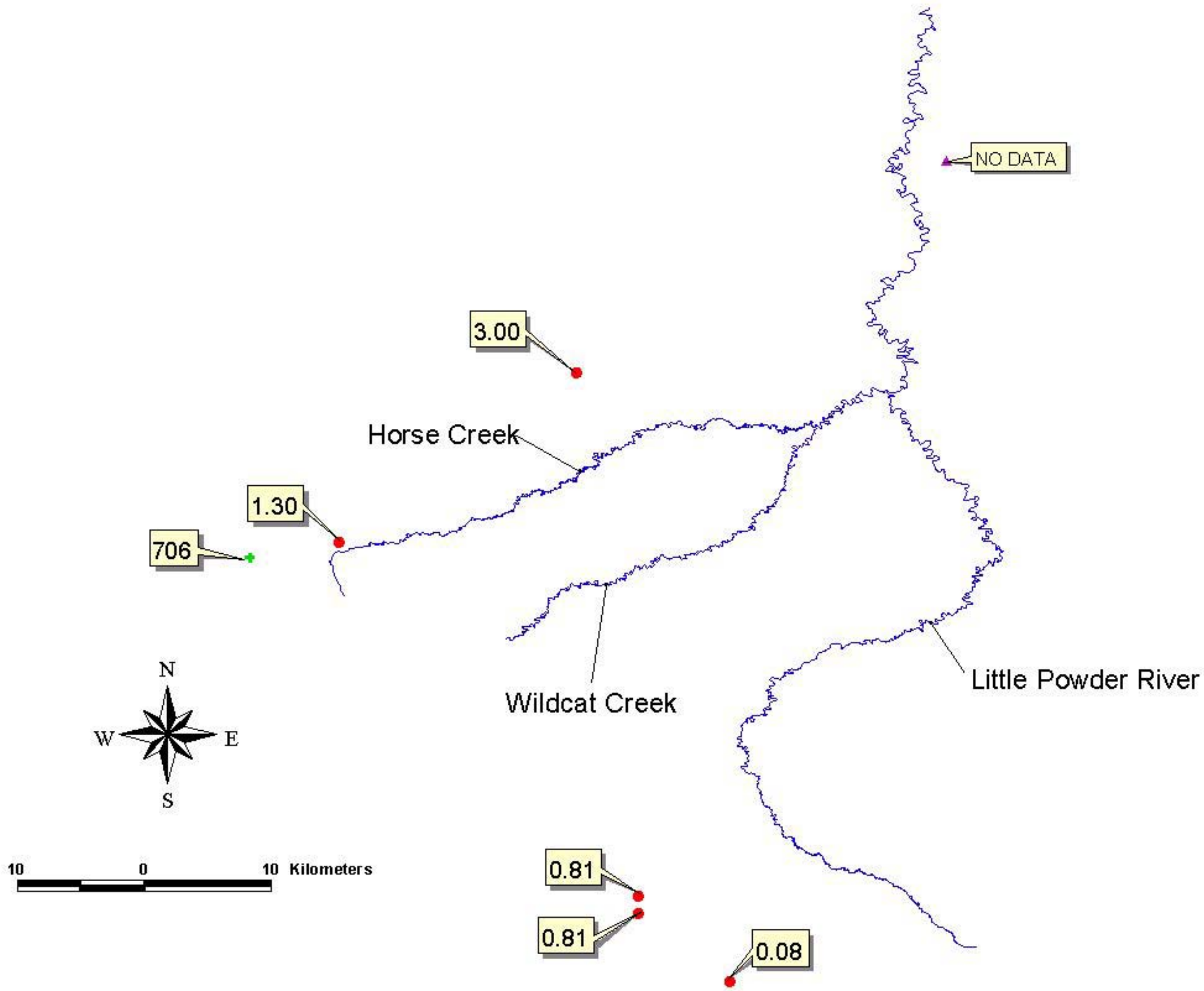

Figure 68. Sulfate concentrations (mg/L) in product water from coalbed methane wells in the Little Powder River drainage, including Horse and Wildcat Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

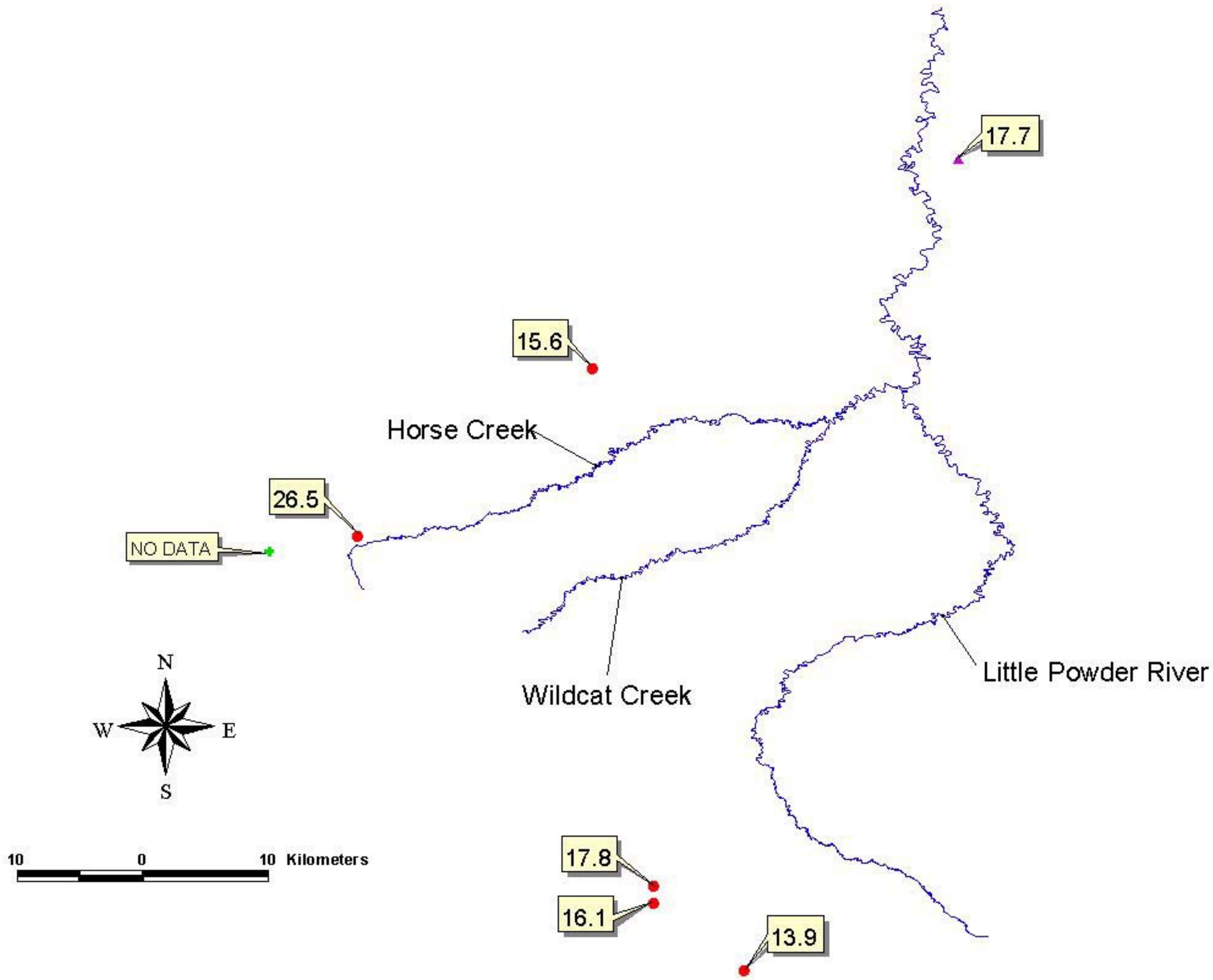

Figure 69. Temperatures (°C) of product water from coalbed methane wells in the Little Powder River drainage, including Horse and Wildcat Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

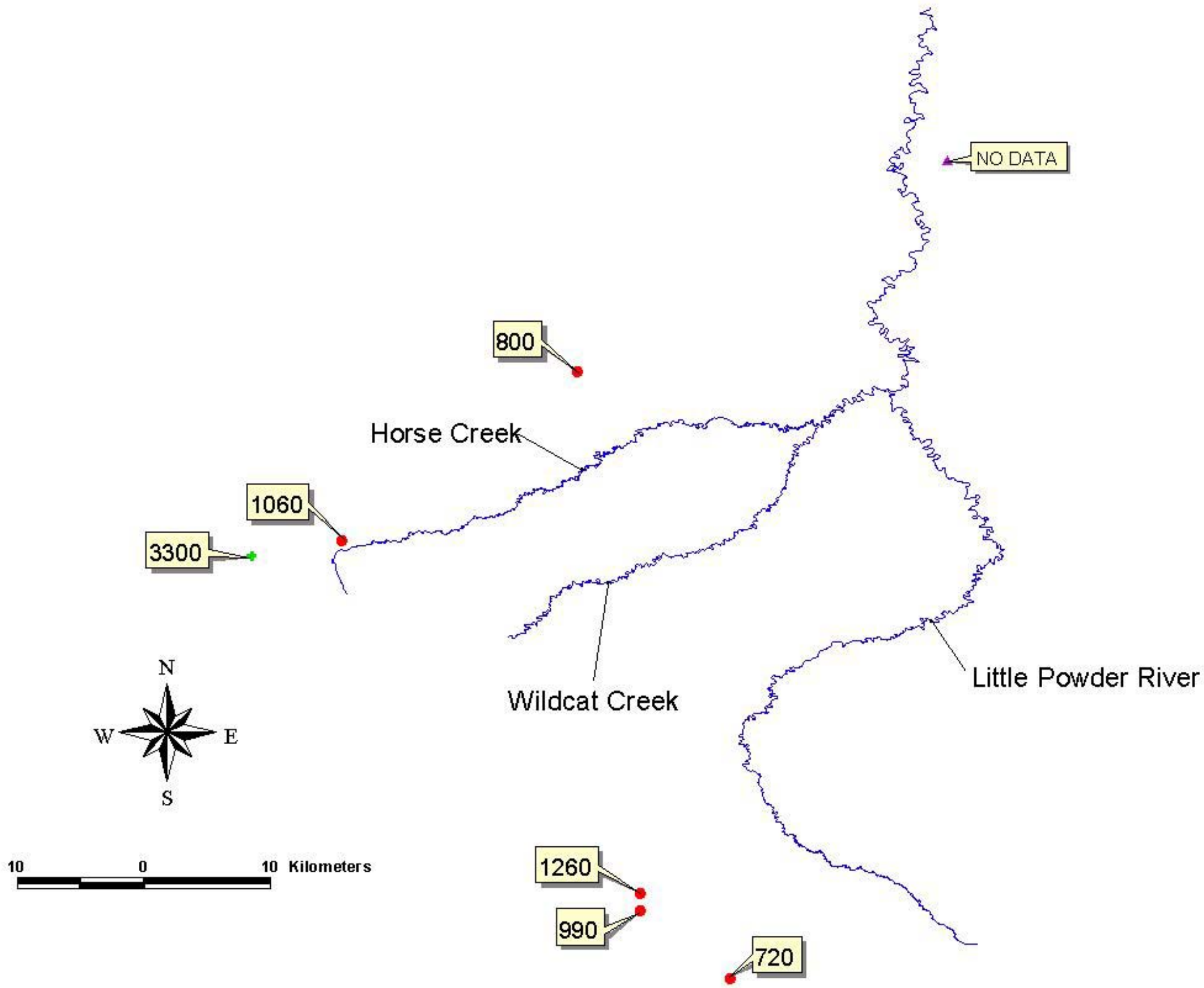

Figure 70. Total dissolved solids concentrations (mg/L) in product water from coalbed methane wells in the Little Powder River drainage, including Horse and Wildcat Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

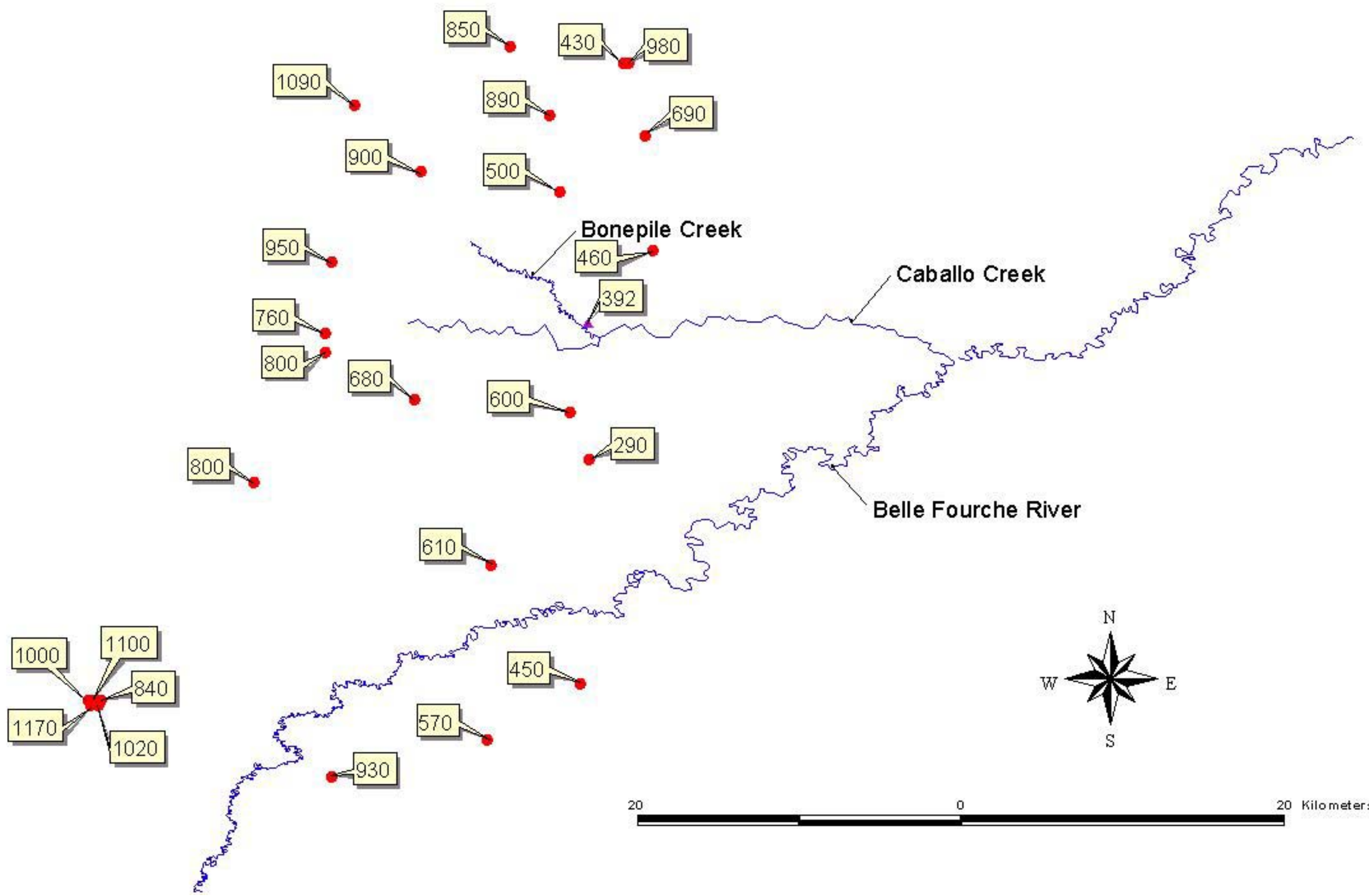

Figure 71. Alkalinity (mg/L as $CaCO_3$) of product water from coalbed methane wells in the Belle Fourche River drainage, including Caballo and Bonepile Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

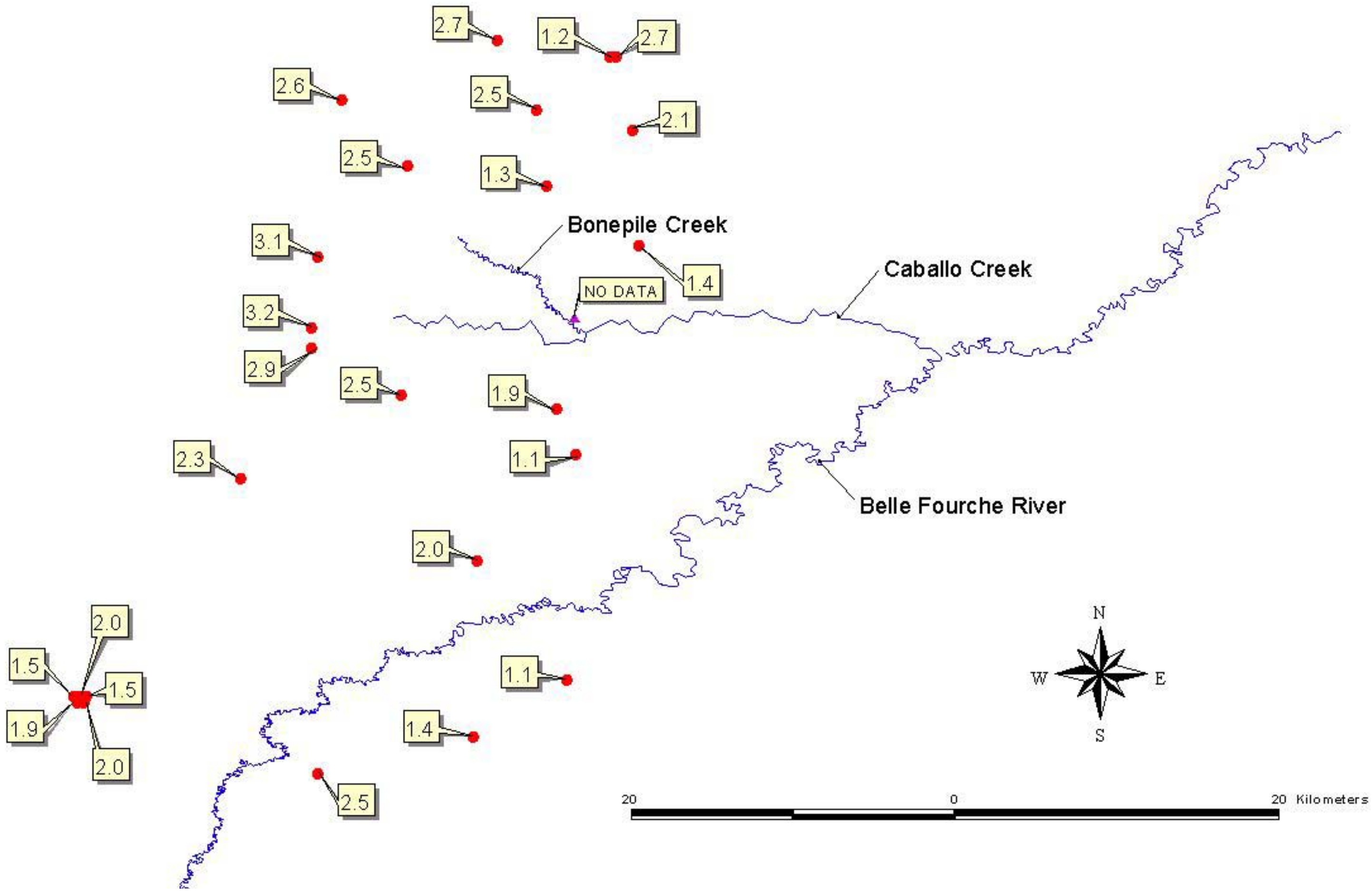

Figure 72. Ammonia concentrations (mg NH_4^+/L) in product water from coalbed methane wells in the Belle Fourche River drainage, including Caballo and Bonepile Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

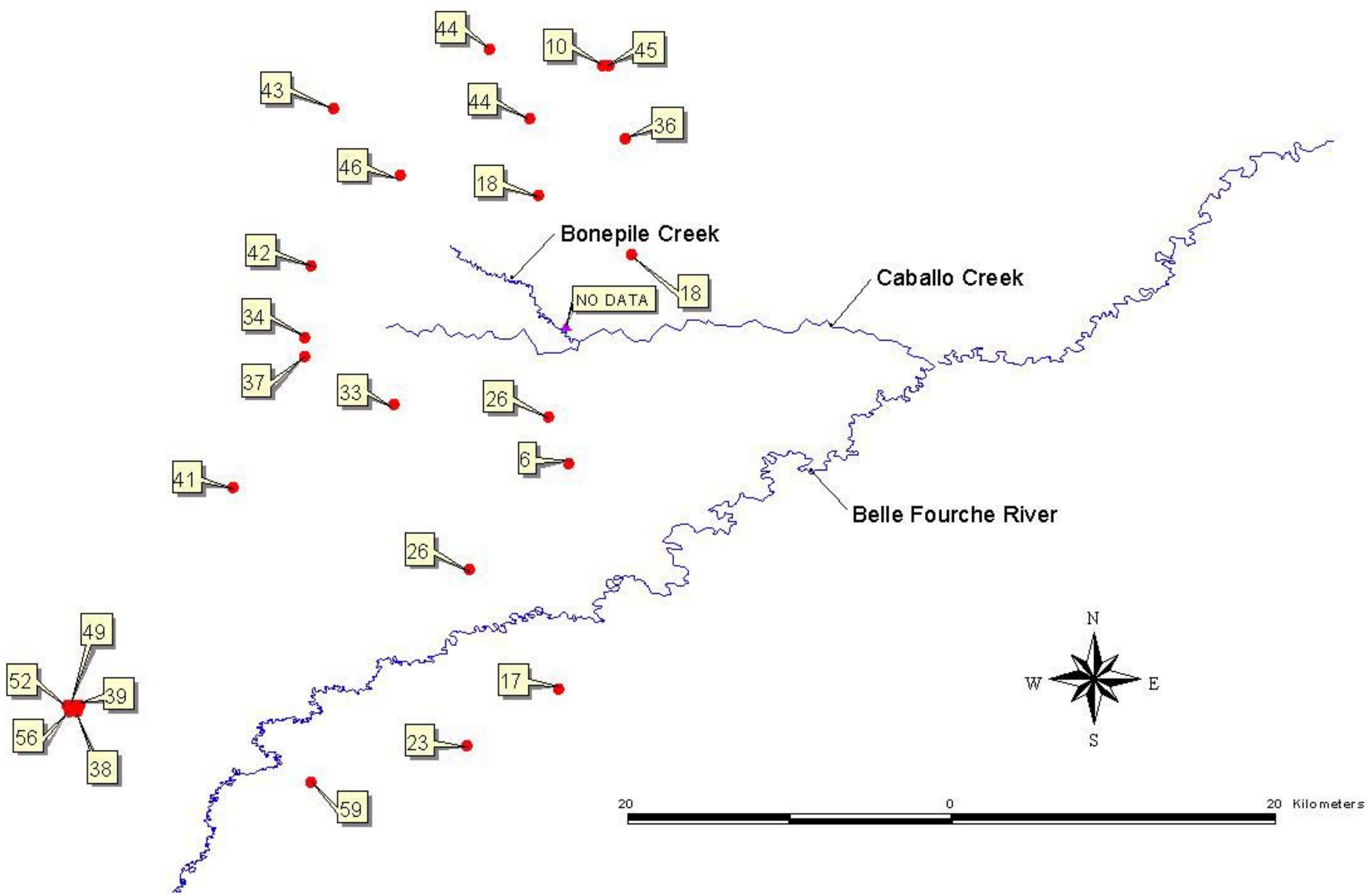

Figure 73. Calcium concentrations (mg/L) in product water from coalbed methane wells in the Belle Fourche River drainage, including Caballo and Bonepile Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

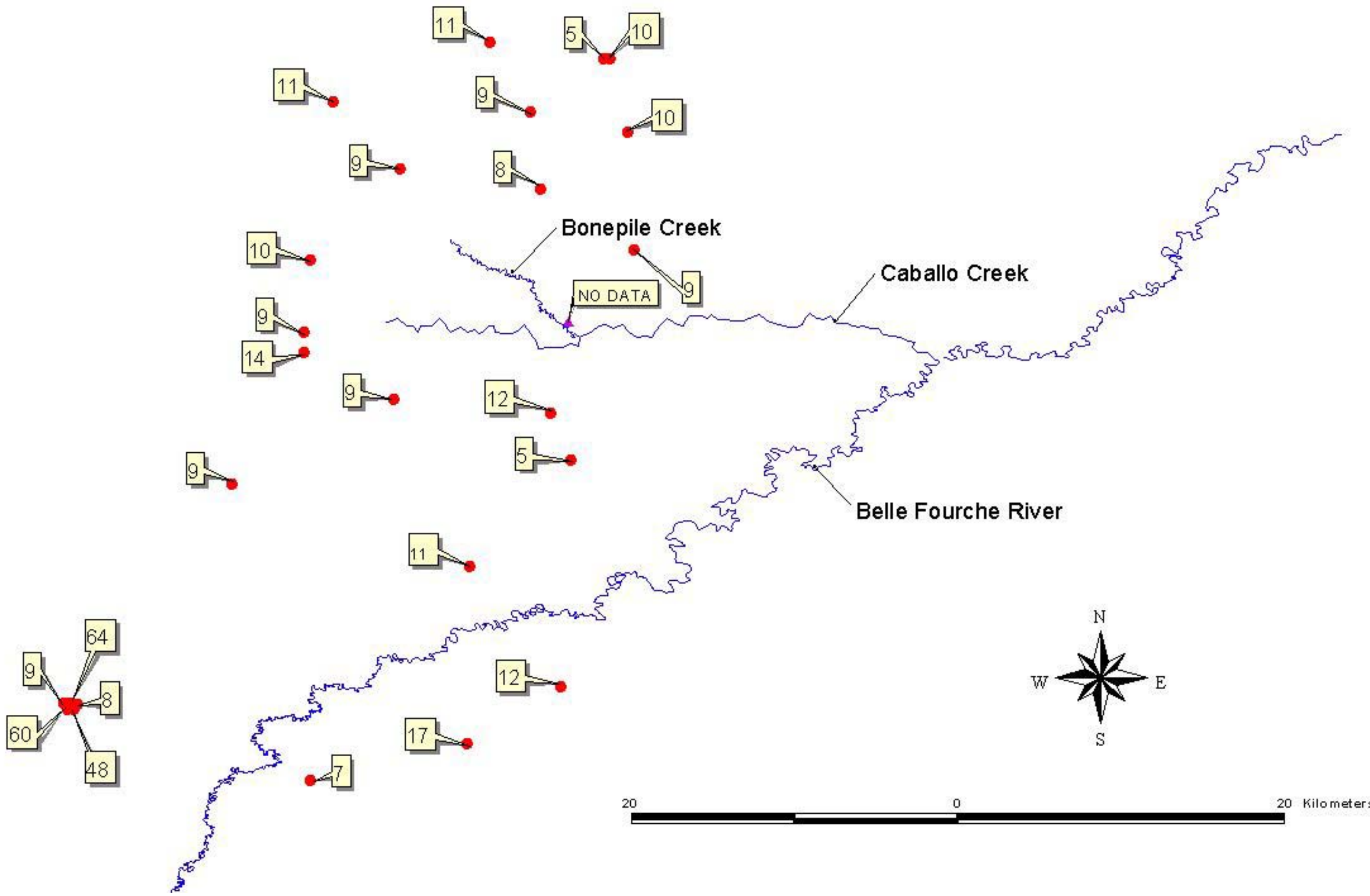

Figure 74. Chloride concentrations (mg/L) in product water from coalbed methane wells in the Belle Fourche River drainage, including Caballo and Bonepile Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

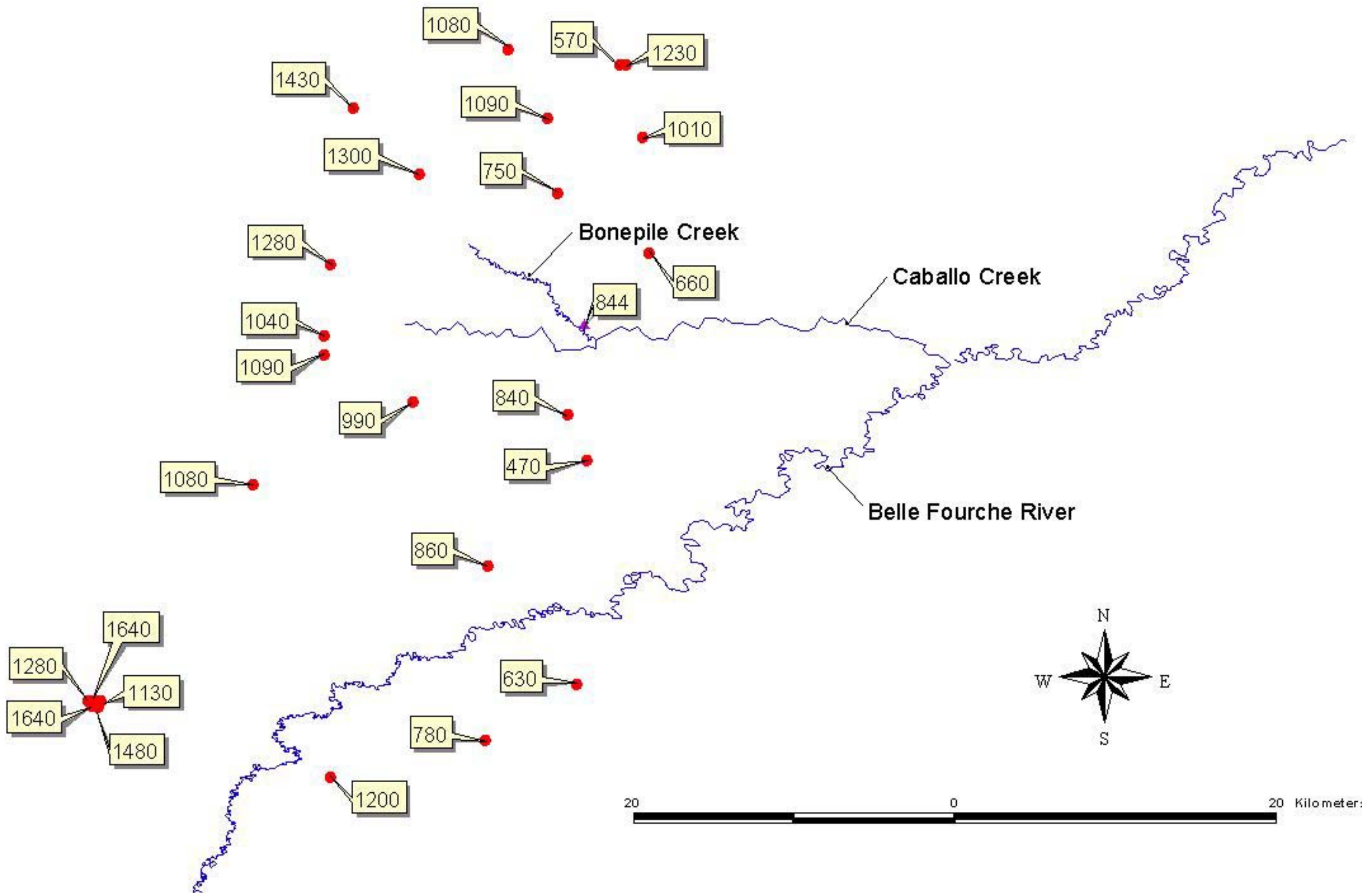

Figure 75. Conductivity (μS/cm) of product water from coalbed methane wells in the Belle Fourche River drainage, including Caballo and Bonepile Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

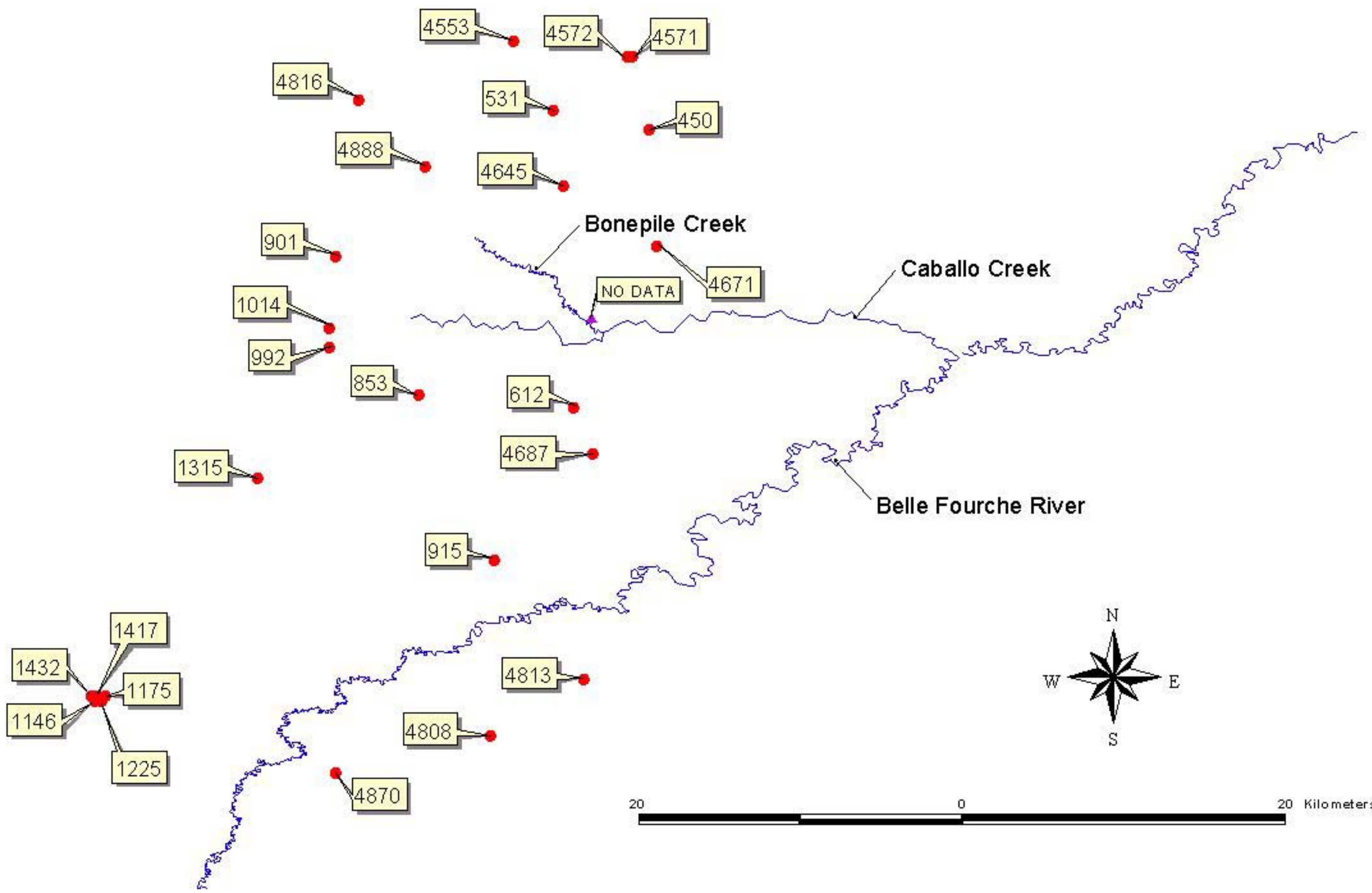

Figure 76. Depth (ft) of coalbed methane wells in the Belle Fourche River drainage, including Caballo and Bonepile Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

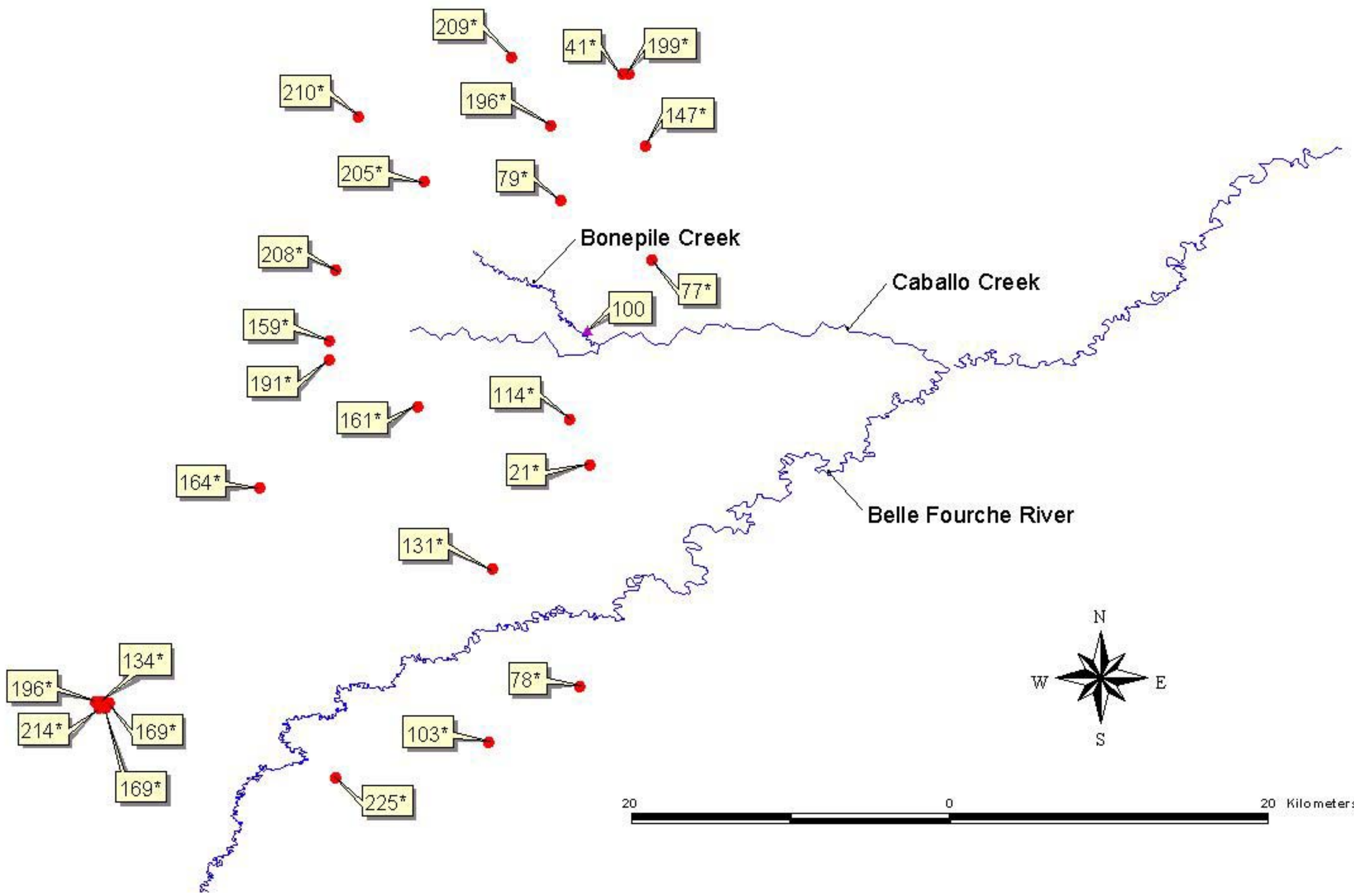

Figure 77. Hardness (mg/L as $CaCO_3$; * indicates values calculated from sum of mEq/L of Ca and Mg) of product water from coalbed methane wells in the Belle Fourche River drainage, including Caballo and Bonepile Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

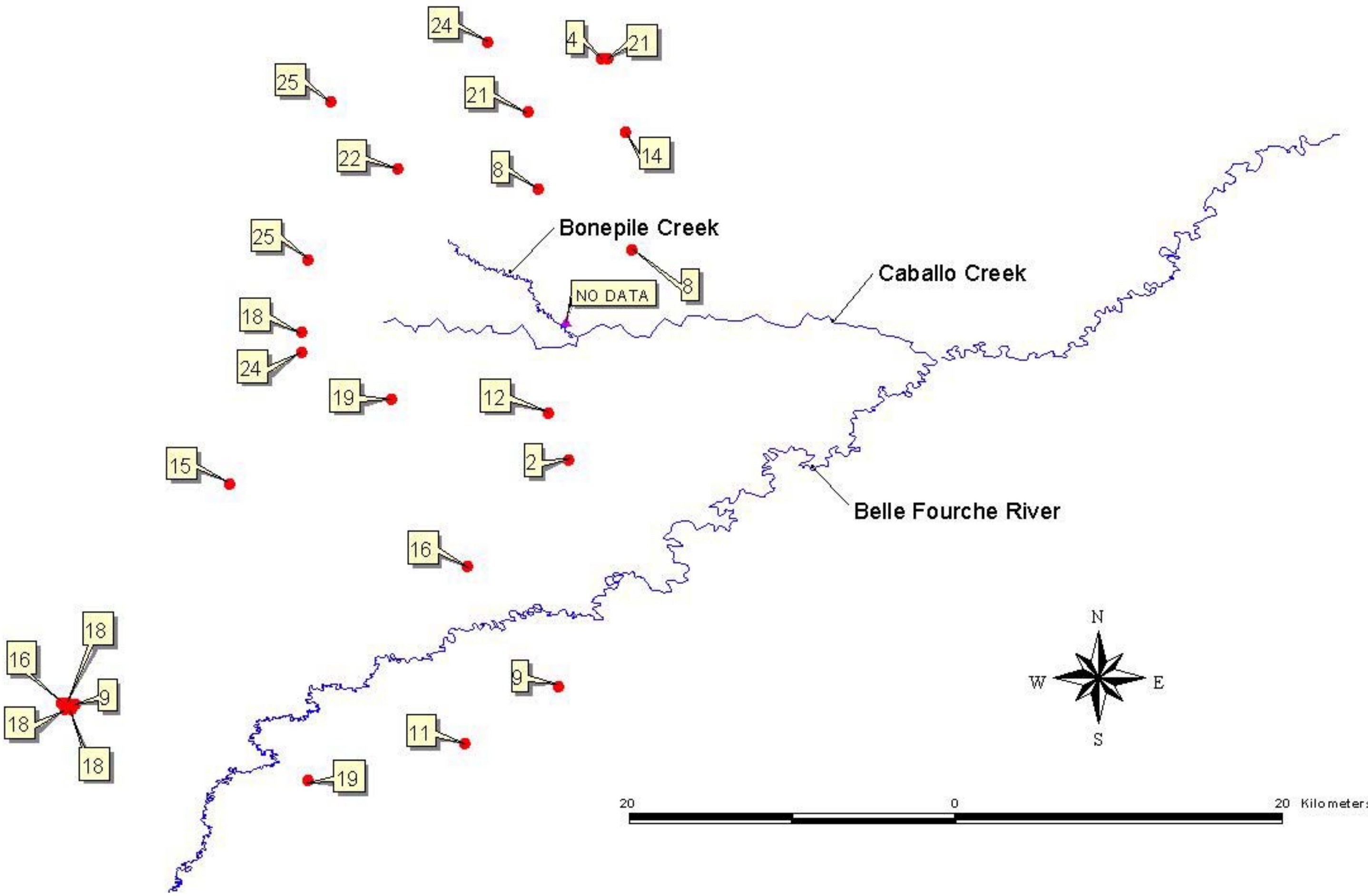

Figure 78. Magnesium concentrations (mg/L) in product water from coalbed methane wells in the Belle Fourche River drainage, including Caballo and Bonepile Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

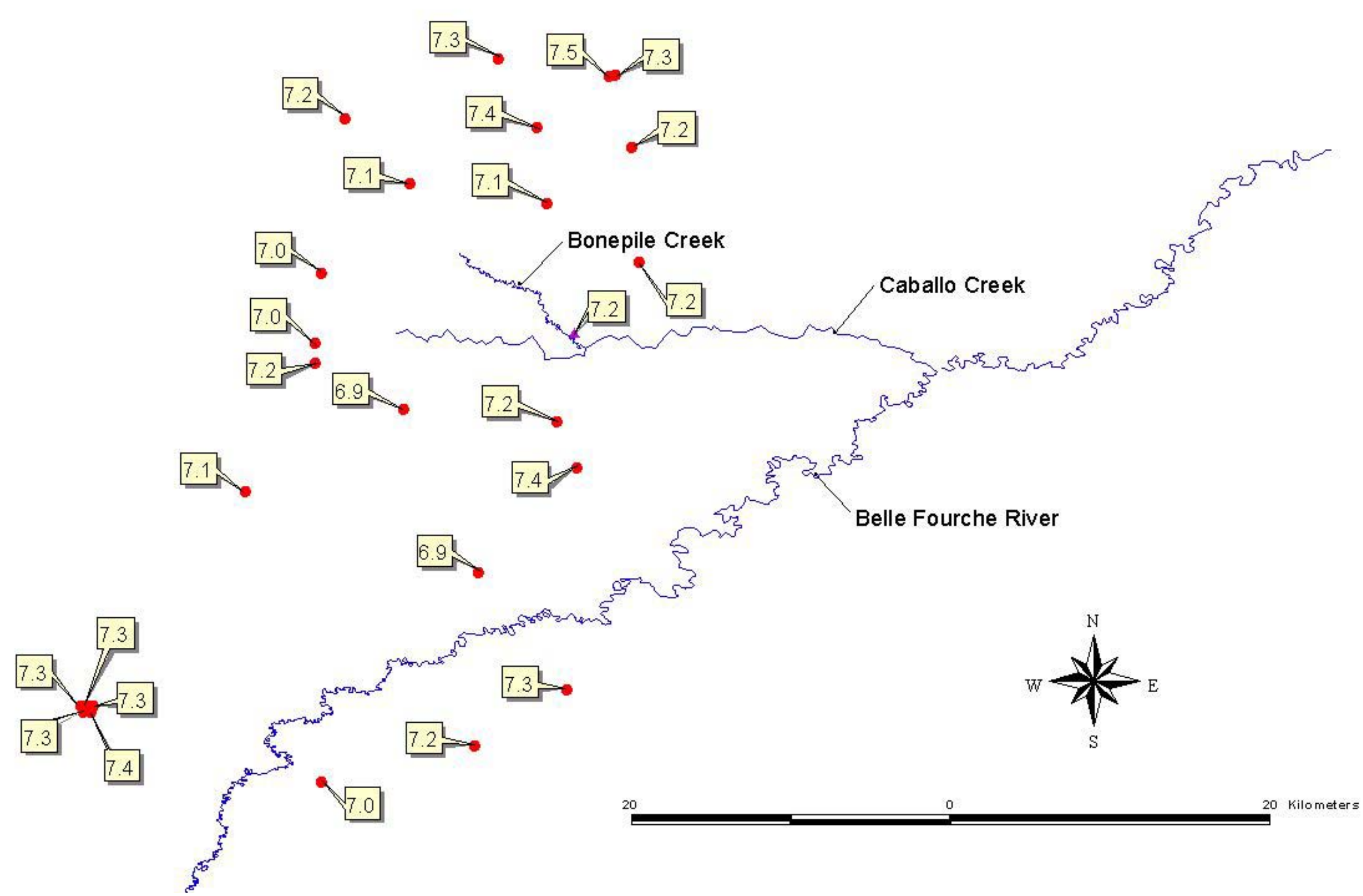

Figure 79. pH (standard units) of product water from coalbed methane wells in the Belle Fourche River drainage, including Caballo and Bonepile Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

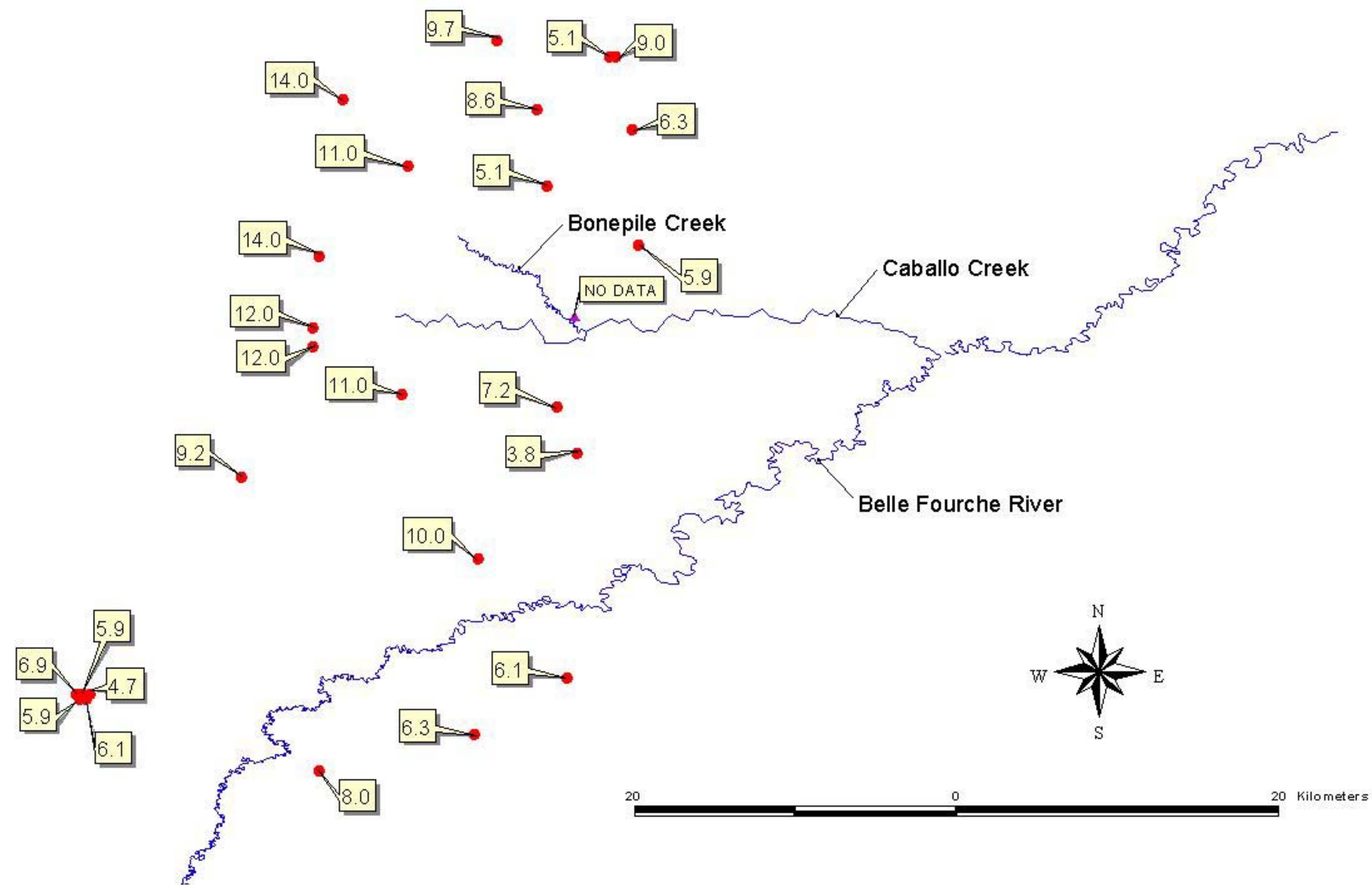

Figure 80. Potassium concentrations (mg/L) in product water from coalbed methane wells in the Belle Fourche River drainage, including Caballo and Bonepile Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

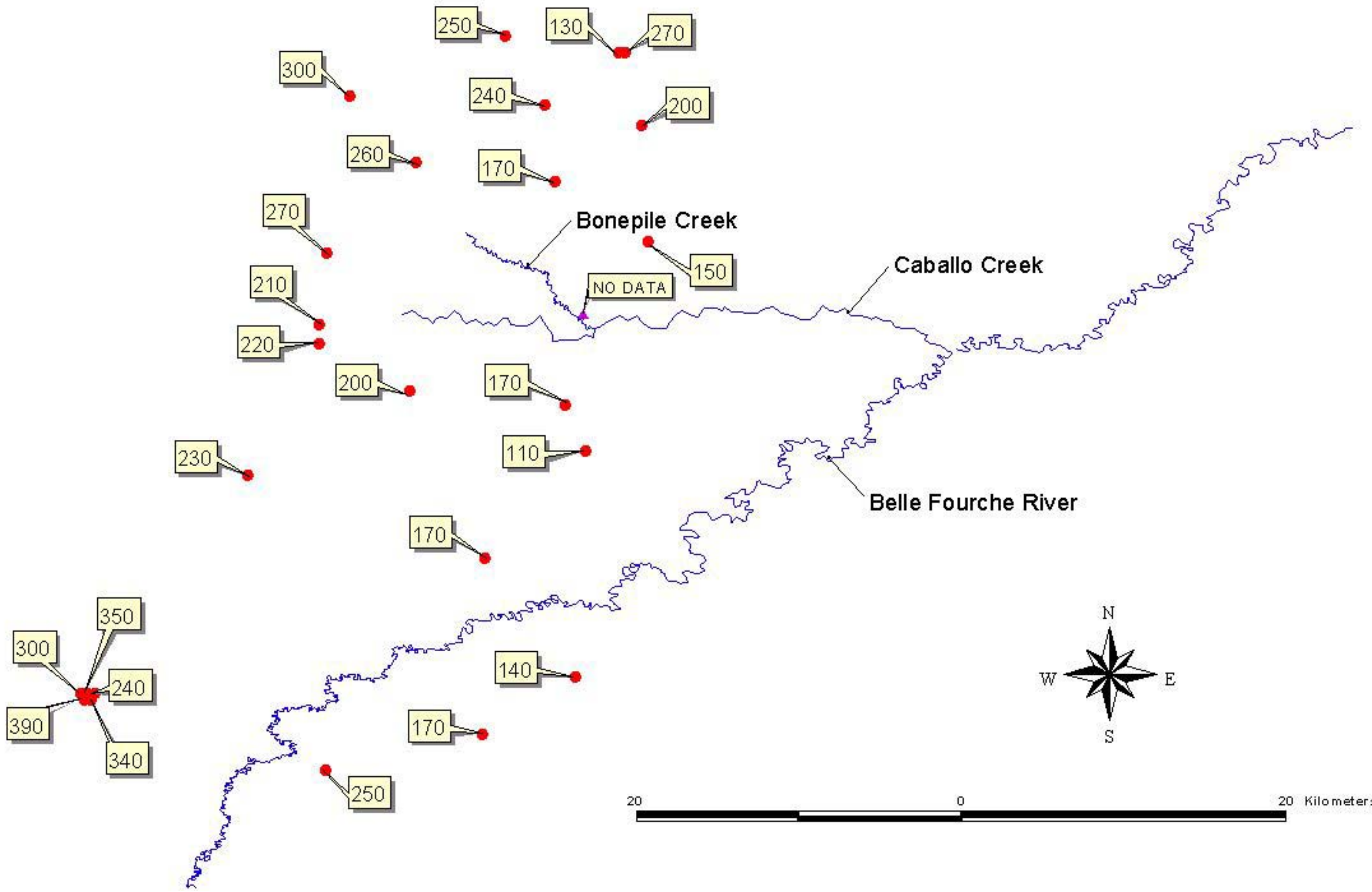

Figure 81. Sodium concentrations (mg/L) in product water from coalbed methane wells in the Belle Fourche River drainage, including Caballo and Bonepile Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

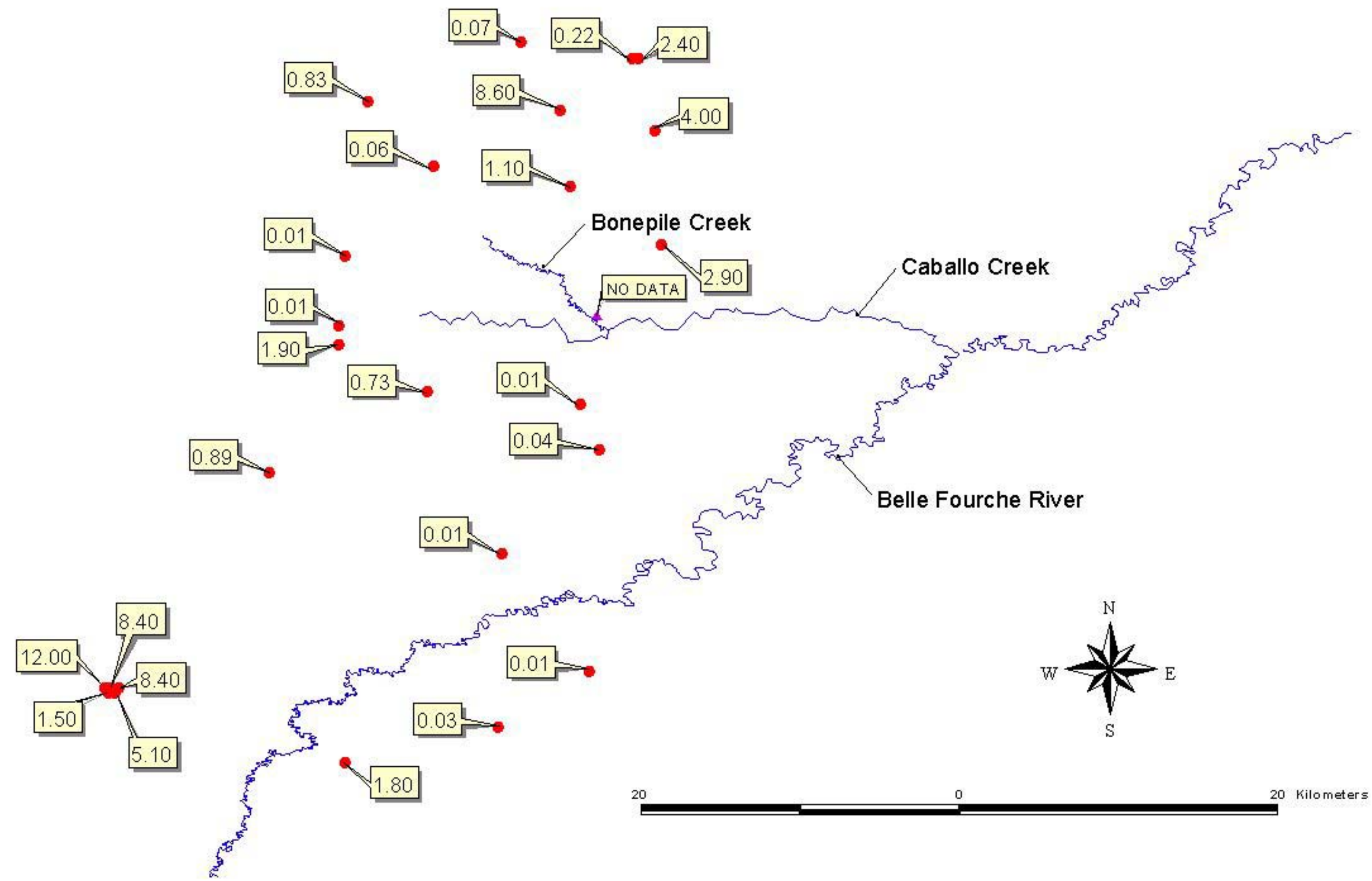

Figure 82. Sulfate concentrations (mg/L) in product water from coalbed methane wells in the Belle Fourche River drainage, including Caballo and Bonepile Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

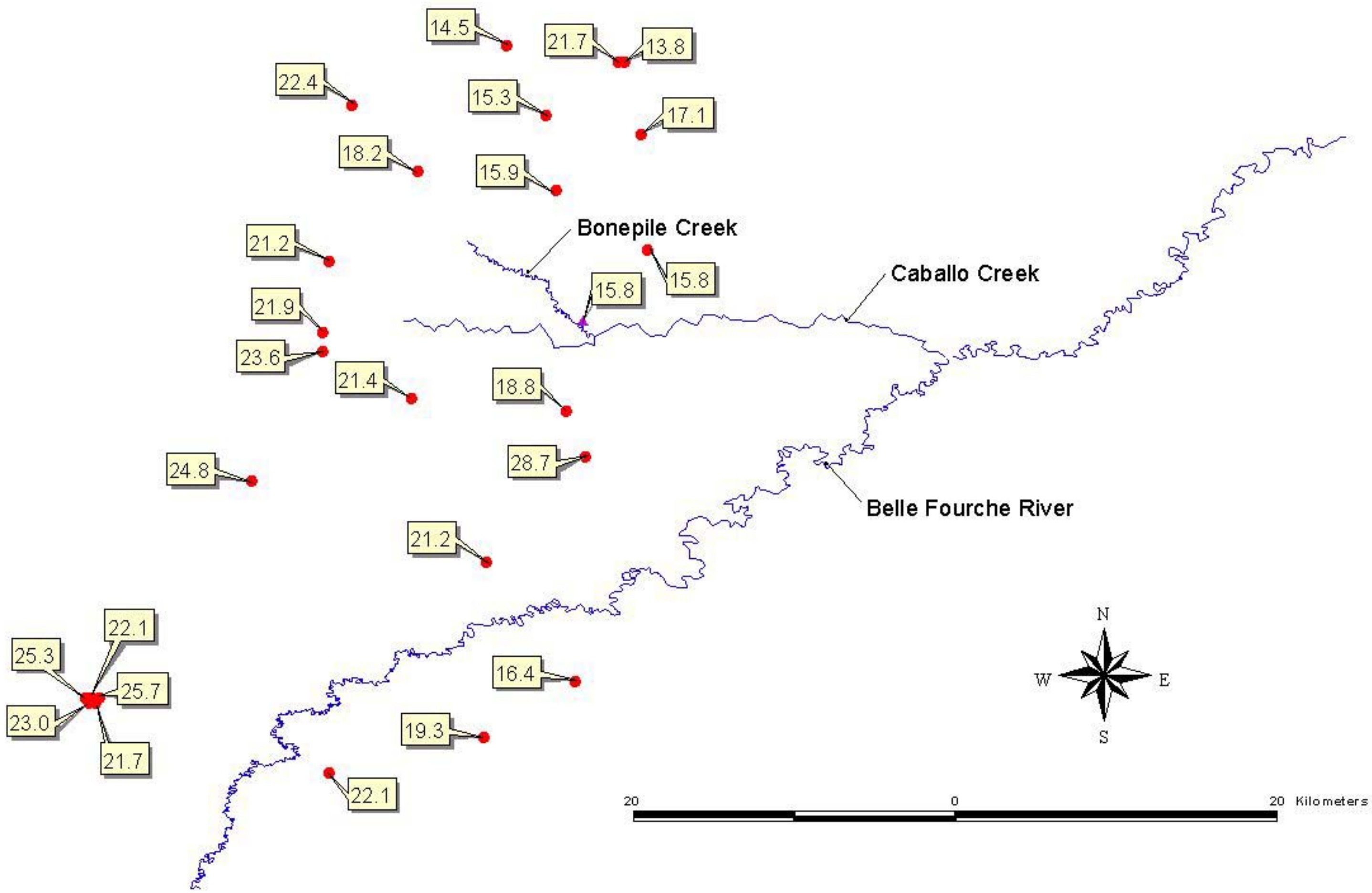

Figure 83. Temperatures (°C) of product water from coalbed methane wells in the Belle Fourche River drainage, including Caballo and Bonepile Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

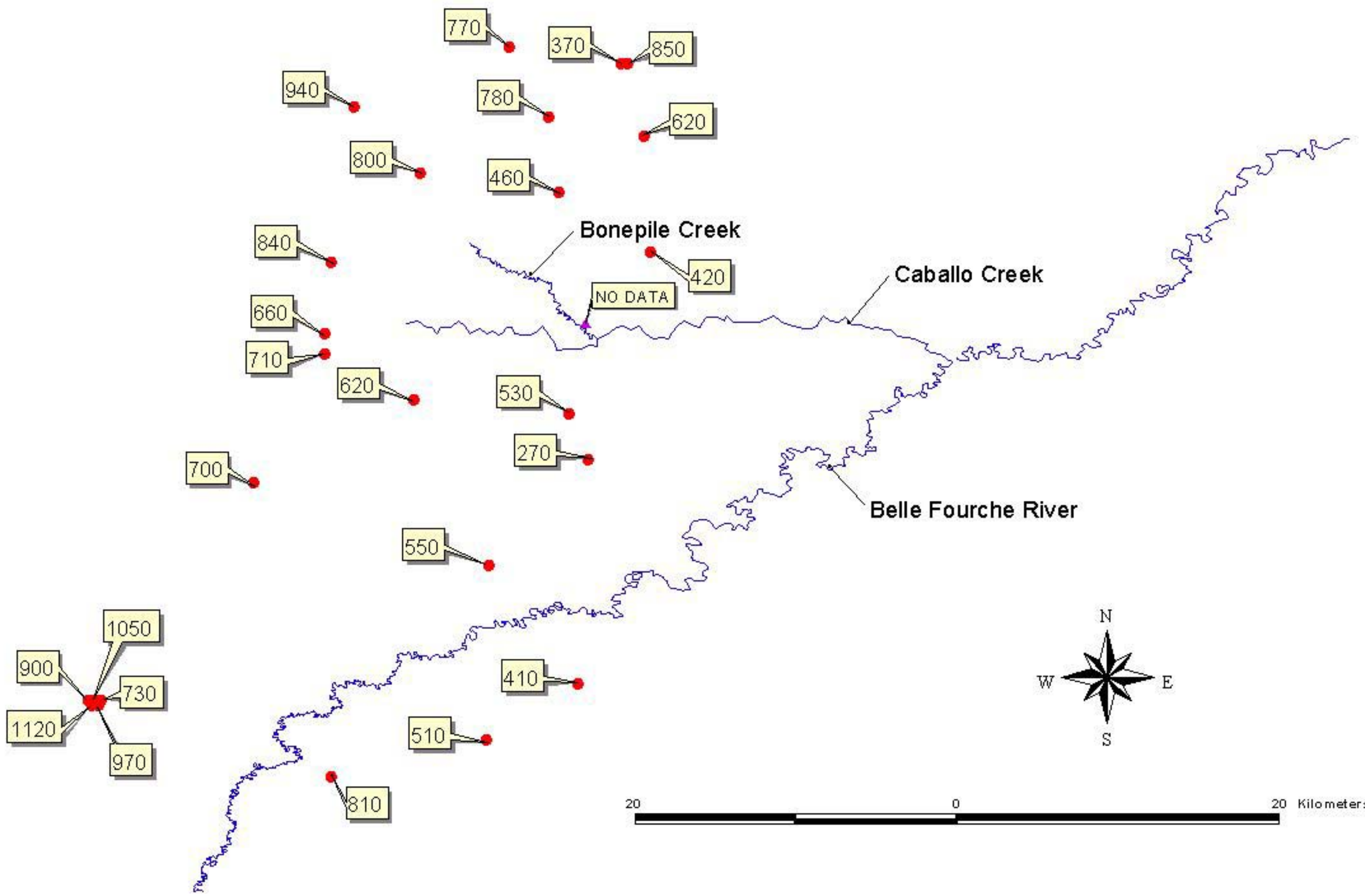

Figure 84. Total dissolved solids concentrations (mg/L) in product water from coalbed methane wells in the Belle Fourche River drainage, including Caballo and Bonepile Creeks. Symbols show well locations and the datasets from which the measurements were taken. Circles indicate dataset A (Rice et al. 2000), squares indicate dataset B (Petroleum Association of Wyoming 2001), crosses indicate dataset C (Wyoming DEQ NPDES permits), and triangles indicate dataset D (Forbes et al. 2001).

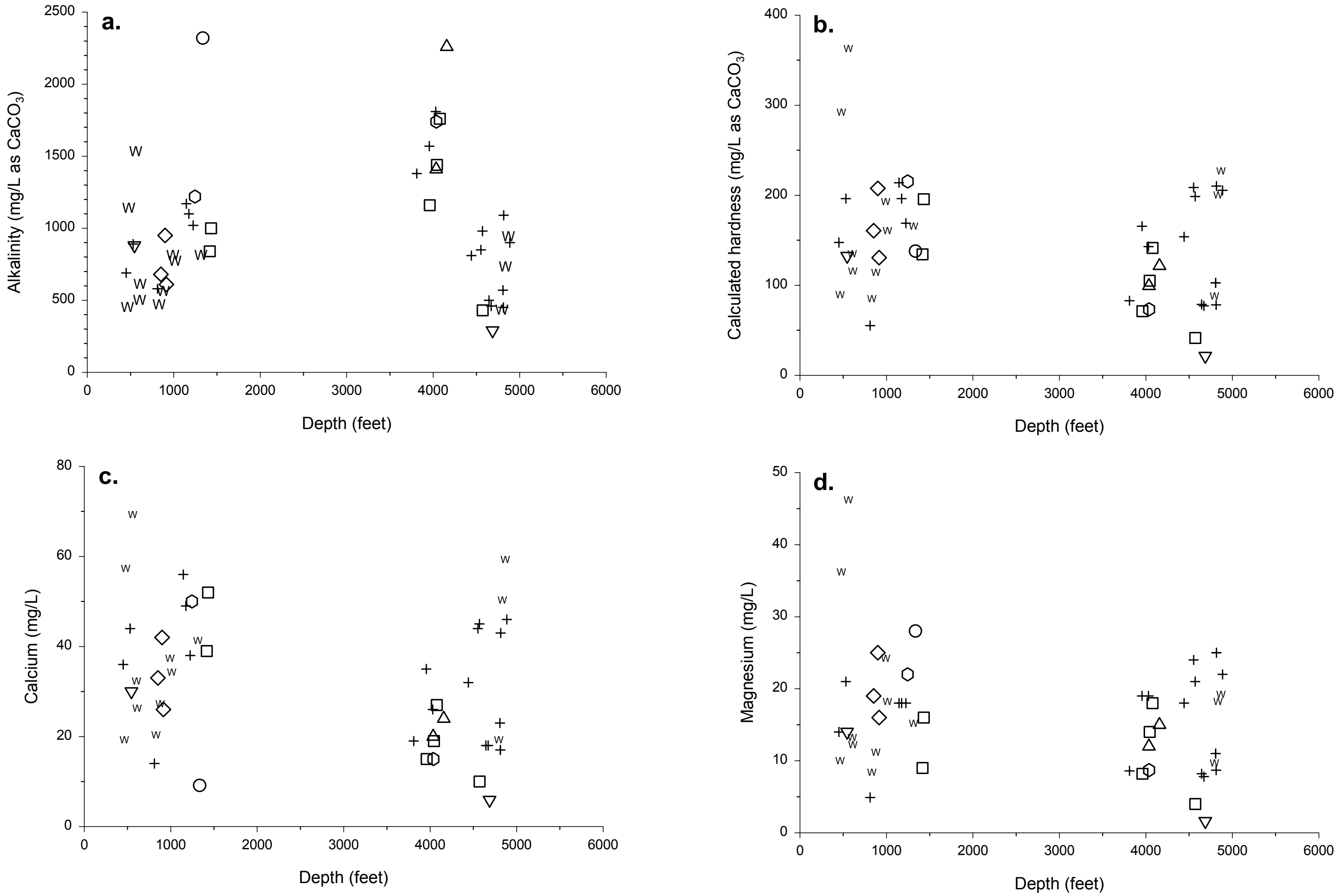

Figure 85. Relationship between (a) alkalinity, (b) hardness (calculated from calcium and magnesium concentrations), (c) calcium concentration, or (d) magnesium concentration and the well depth and geologic formation from which coalbed methane product water samples were collected. Squares = Canyon Formation, hexagons = Wall Formation, diamonds = Fort Union Formation, crosses = Anderson Formation, upward triangles = Cook Formation, downward triangles = Pawnee Formation, W = Wyodak Formation, and circles = Big George Formation.

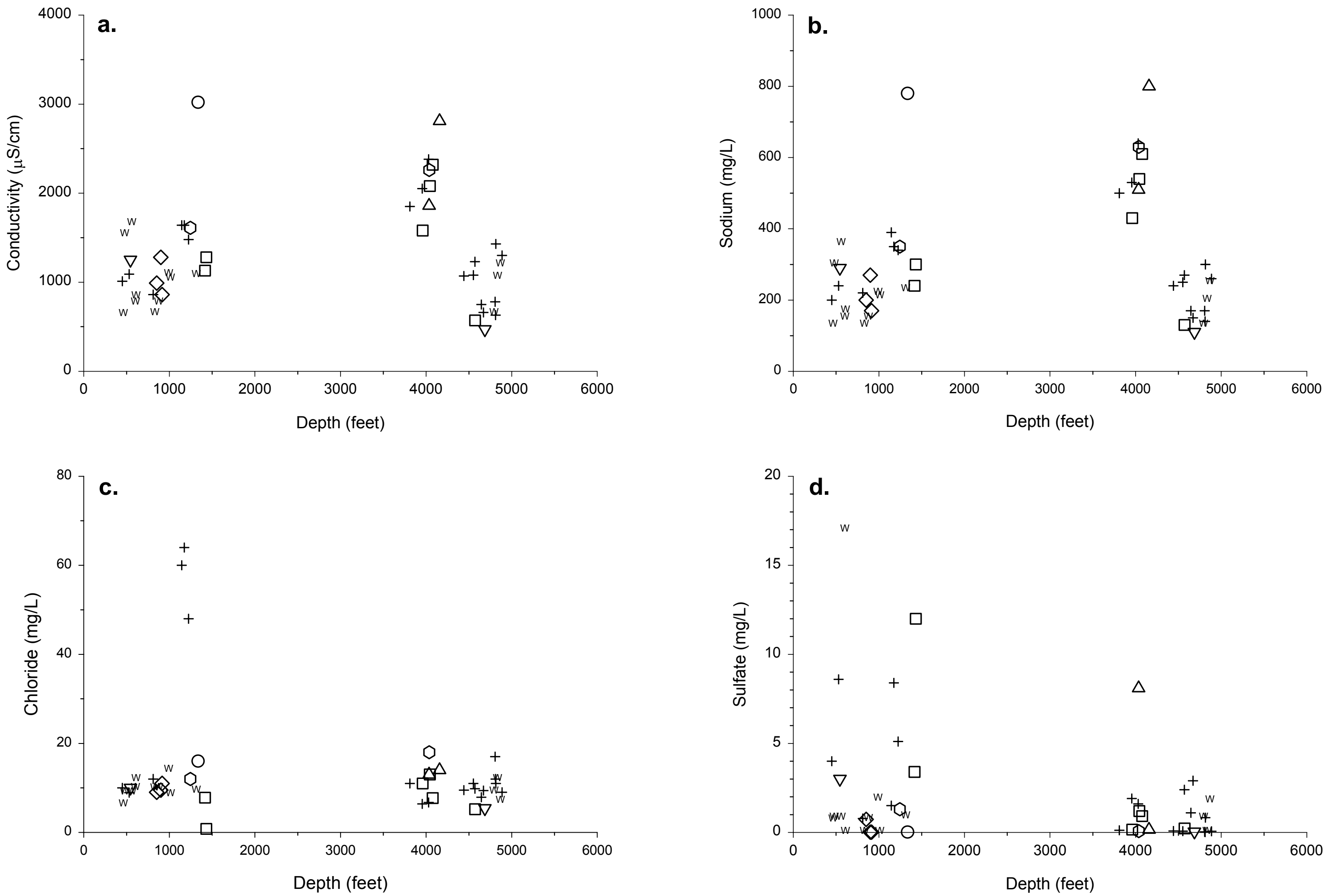

Figure 86. Relationship between (a) conductivity, (b) sodium concentration, (c) chloride concentration, or (d) sulfate concentration and the well depth and geologic formation from which coalbed methane product water samples were collected. Squares = Canyon Formation, hexagons = Wall Formation, diamonds = Fort Union Formation, crosses = Anderson Formation, upward triangles = Cook Formation, downward triangles = Pawnee Formation, W = Wyodak Formation, and circles = Big George Formation.

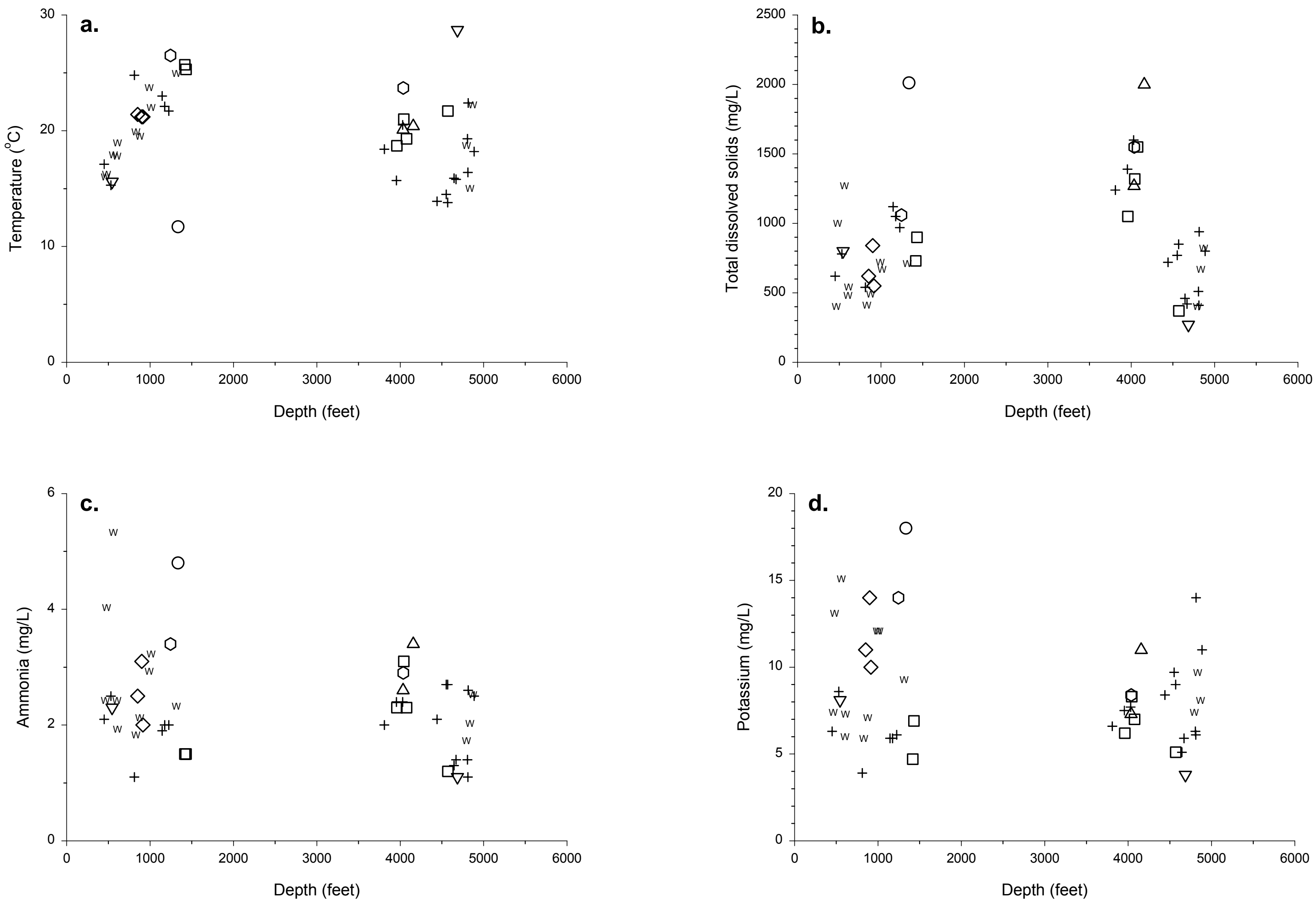

Figure 87. Relationship between (a) temperature, (b) total dissolved solids concentration, (c) ammonia concentration, or (d) potassium concentration and the well depth and geologic formation from which coalbed methane product water samples were collected. Squares = Canyon Formation, hexagons = Wall Formation, diamonds = Fort Union Formation, crosses = Anderson Formation, upward triangles = Cook Formation, downward triangles = Pawnee Formation, W = Wyodak Formation, and circles = Big George Formation.

Appendix A

Seasonal Changes in Surface Water Quality Parameters

Measured at the Tongue River Downstream USGS Site:

1974-1983

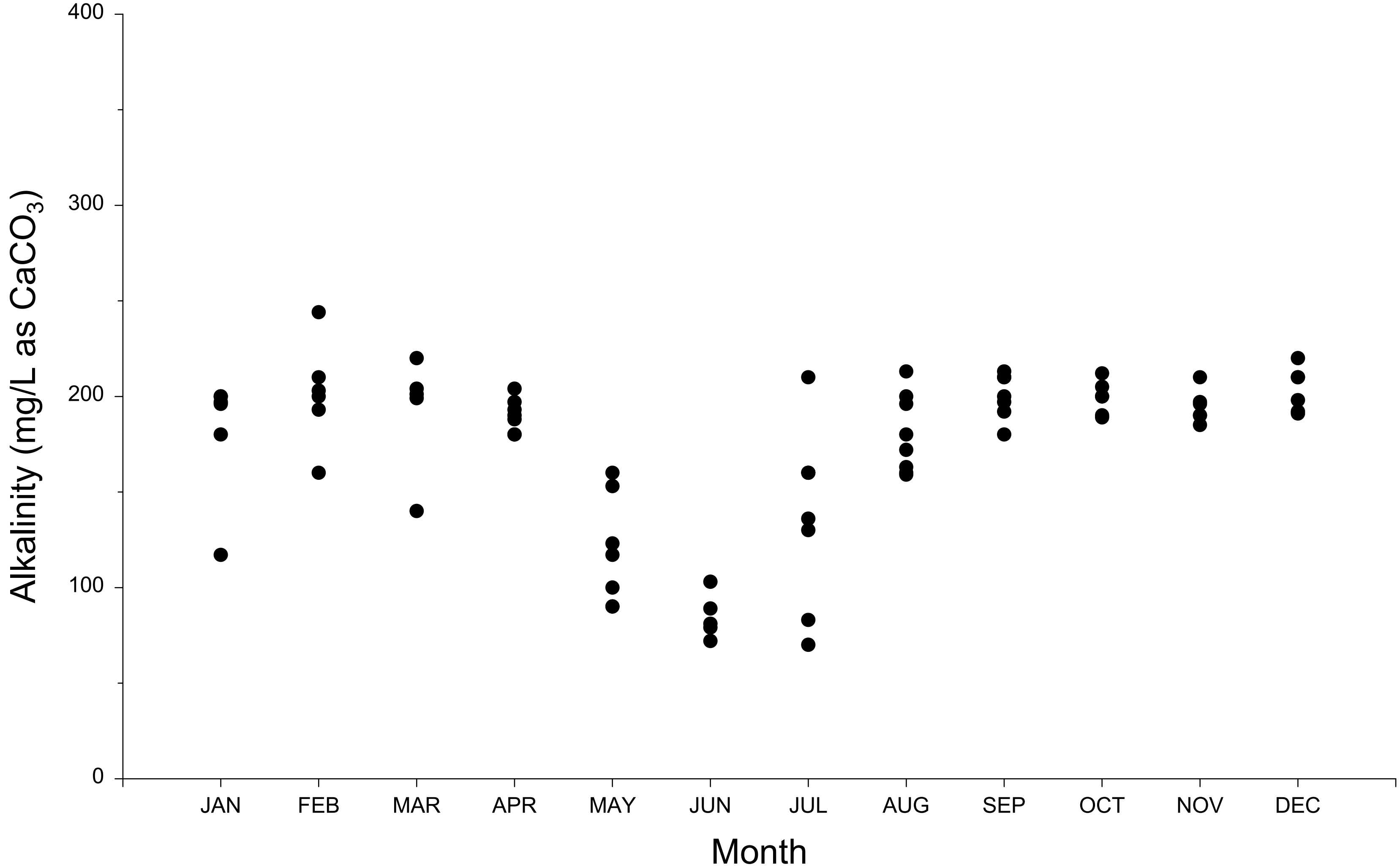

Figure A-1. Seasonal changes in alkalinity of surface water at the Tongue River Downstream site (USGS Site #06299980), from 1974 to 1983.

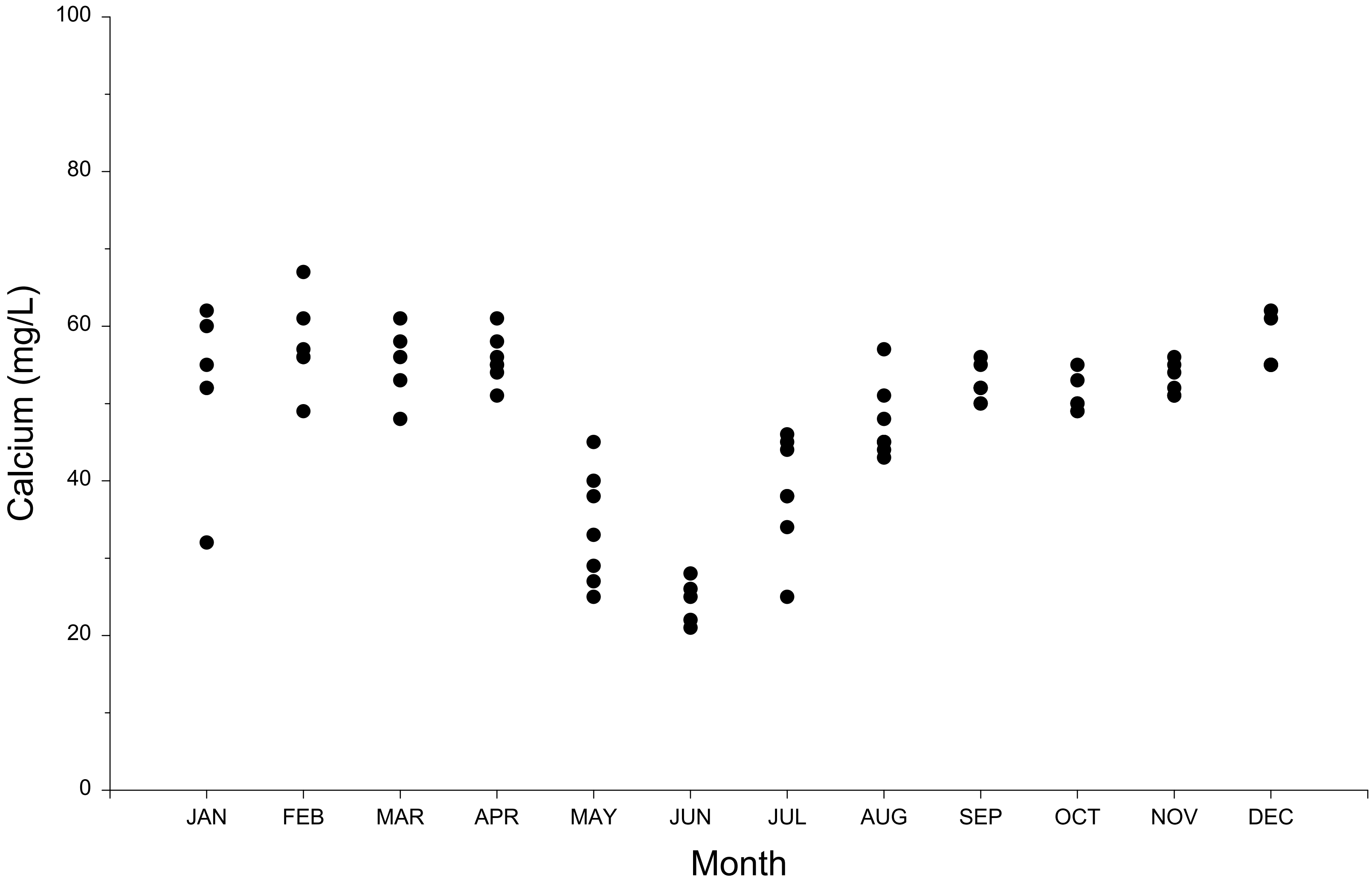

Figure A-2. Seasonal changes in calcium concentration of surface water at the Tongue River Downstream site (USGS Site #06299980), from 1974 to 1983.

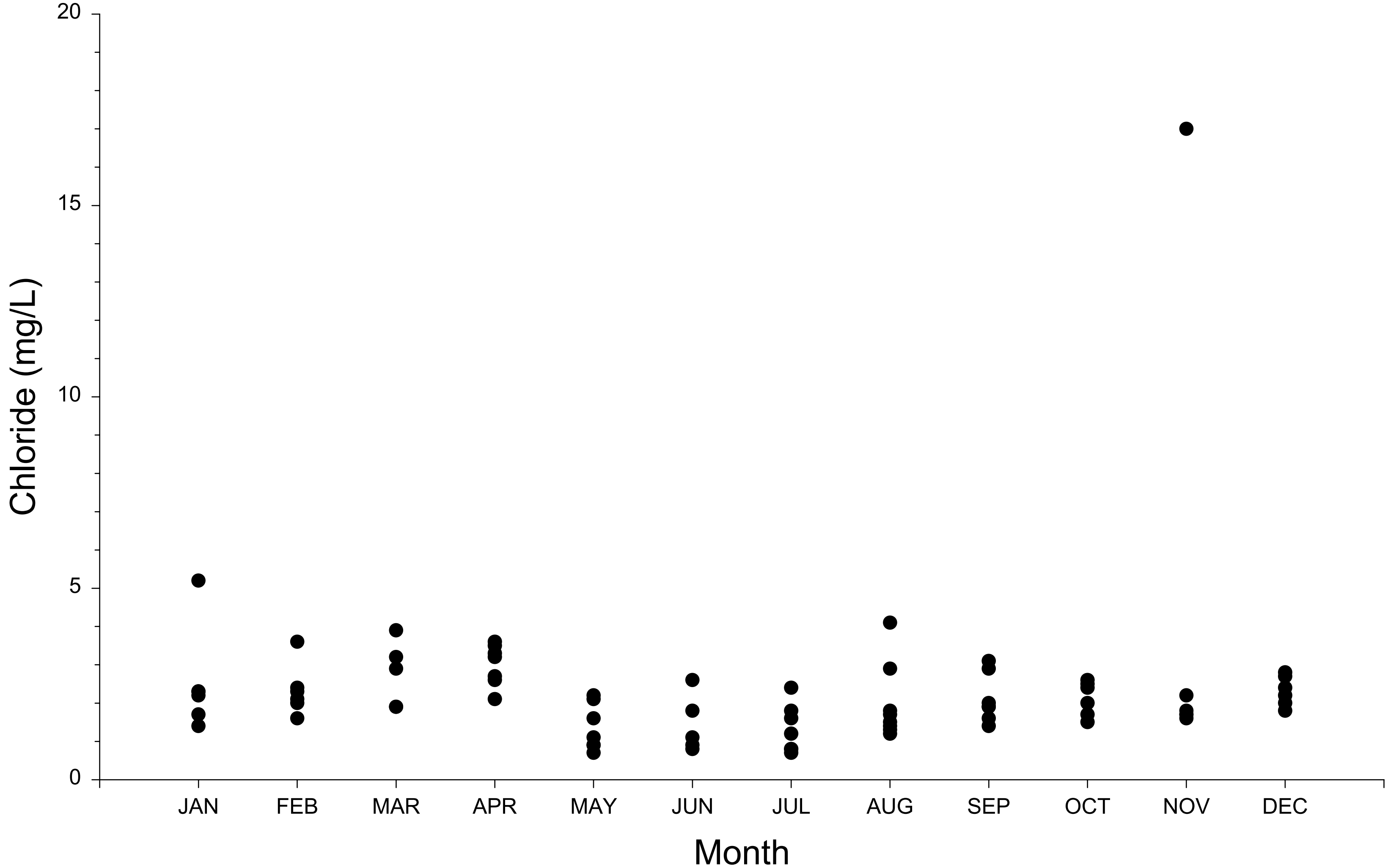

Figure A-3. Seasonal changes in chloride concentration of surface water at the Tongue River Downstream site (USGS Site #06299980), from 1974 to 1983.

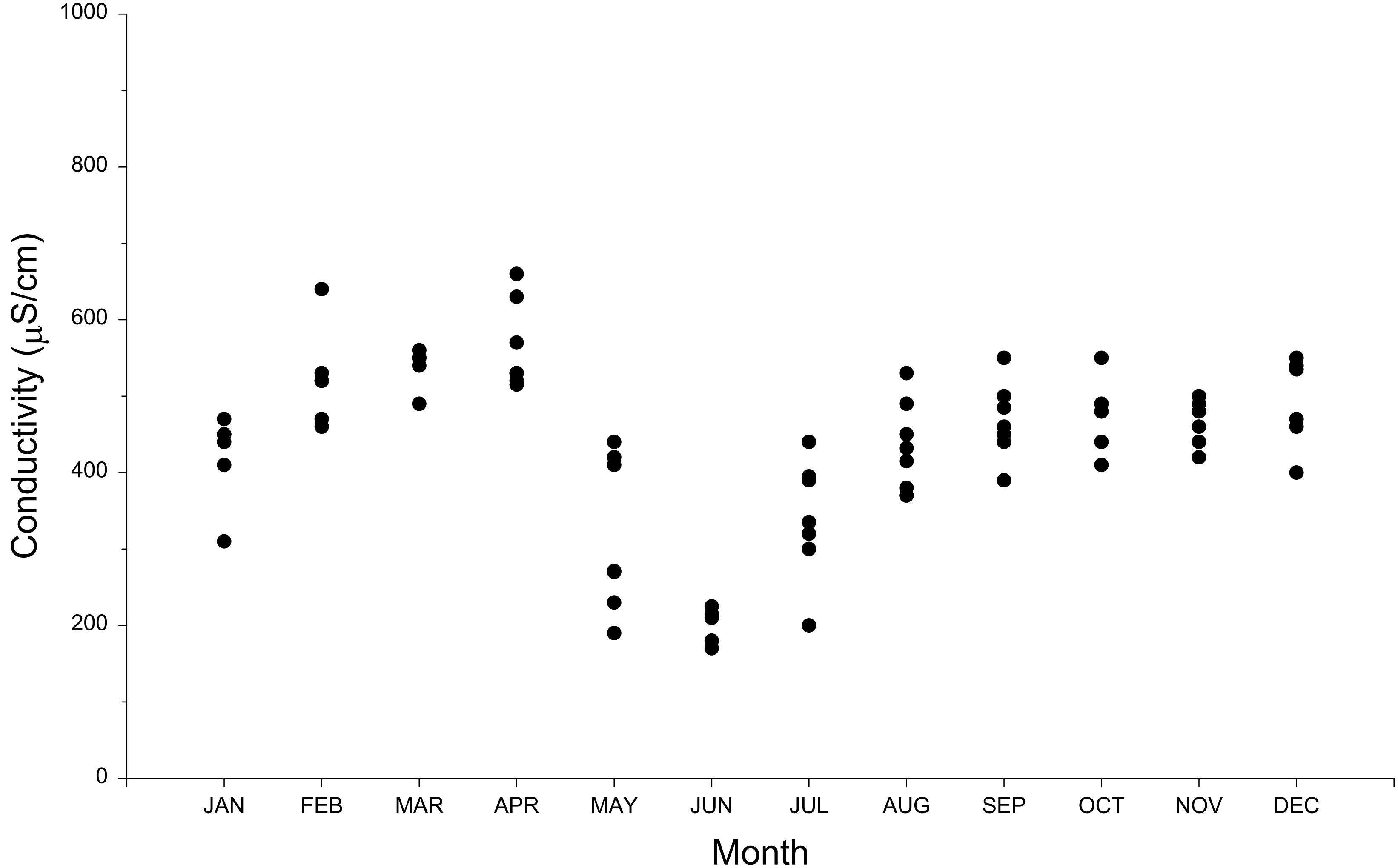

Figure A-4. Seasonal changes in conductivity of surface water at the Tongue River Downstream site (USGS Site #06299980), from 1974 to 1983.

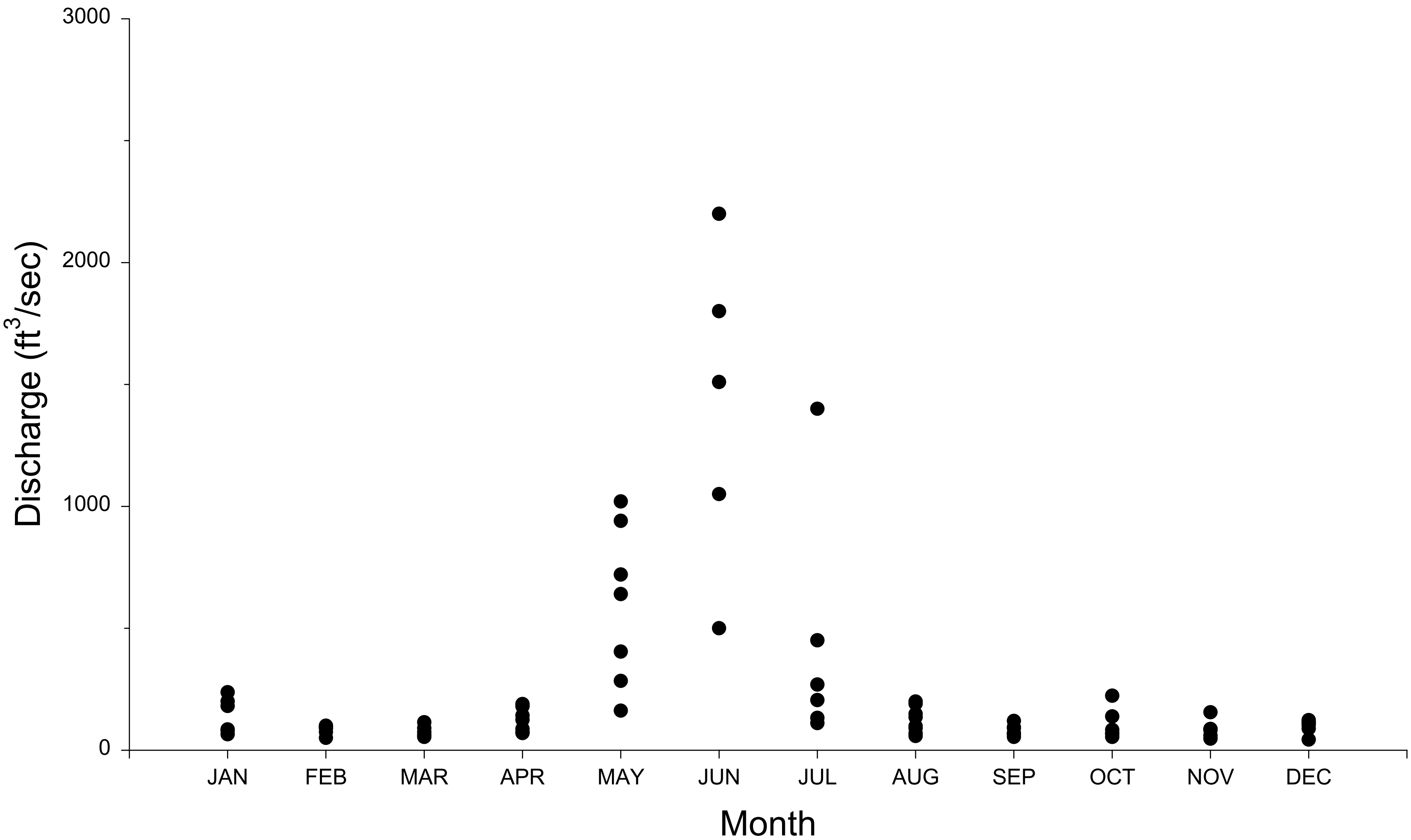

Figure A-5. Seasonal changes in discharge of surface water at the Tongue River Downstream site (USGS Site #06299980), from 1974 to 1983.

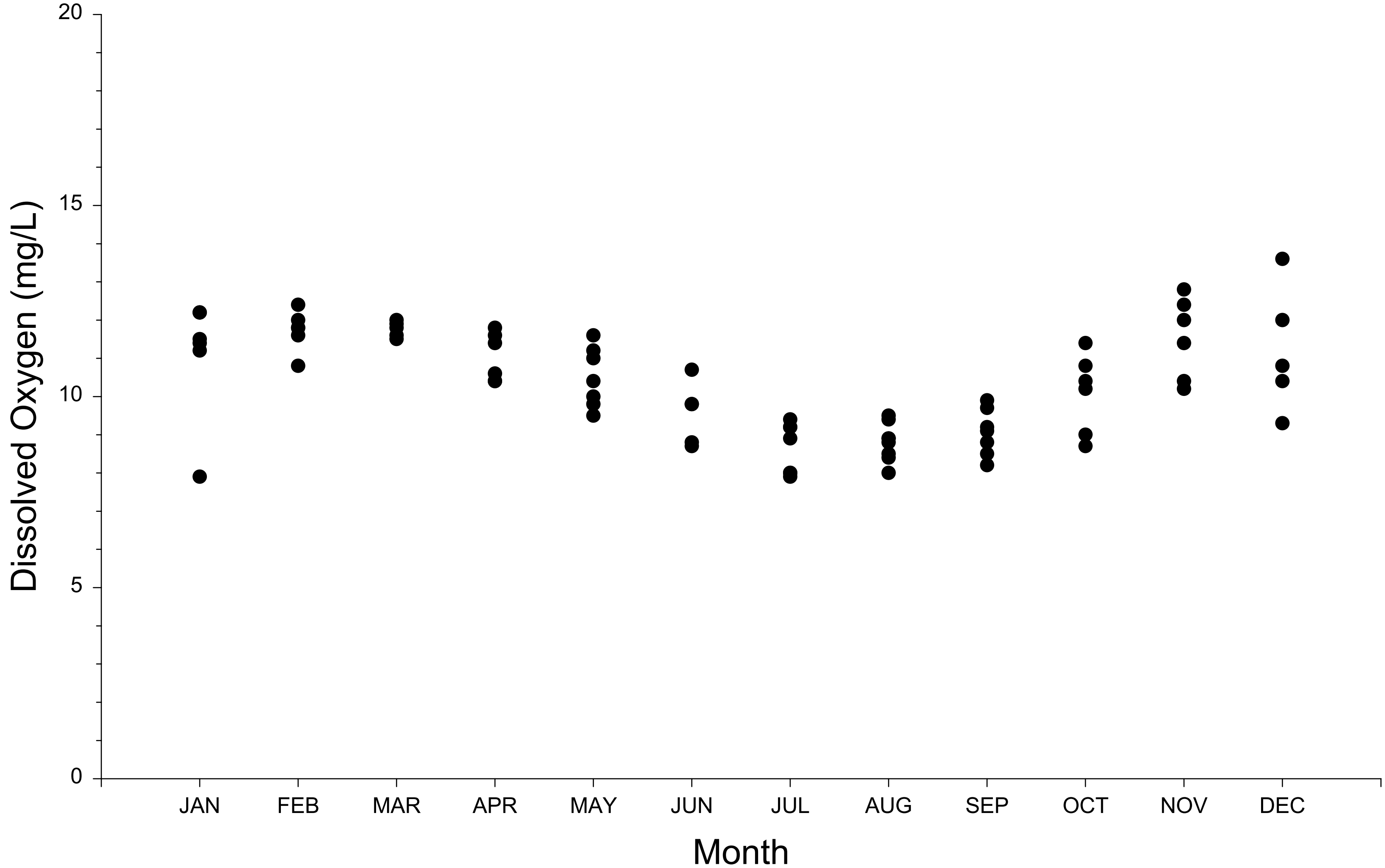

Figure A-6. Seasonal changes in dissolved oxygen concentration of surface water at the Tongue River Downstream site (USGS Site #06299980), from 1974 to 1983.

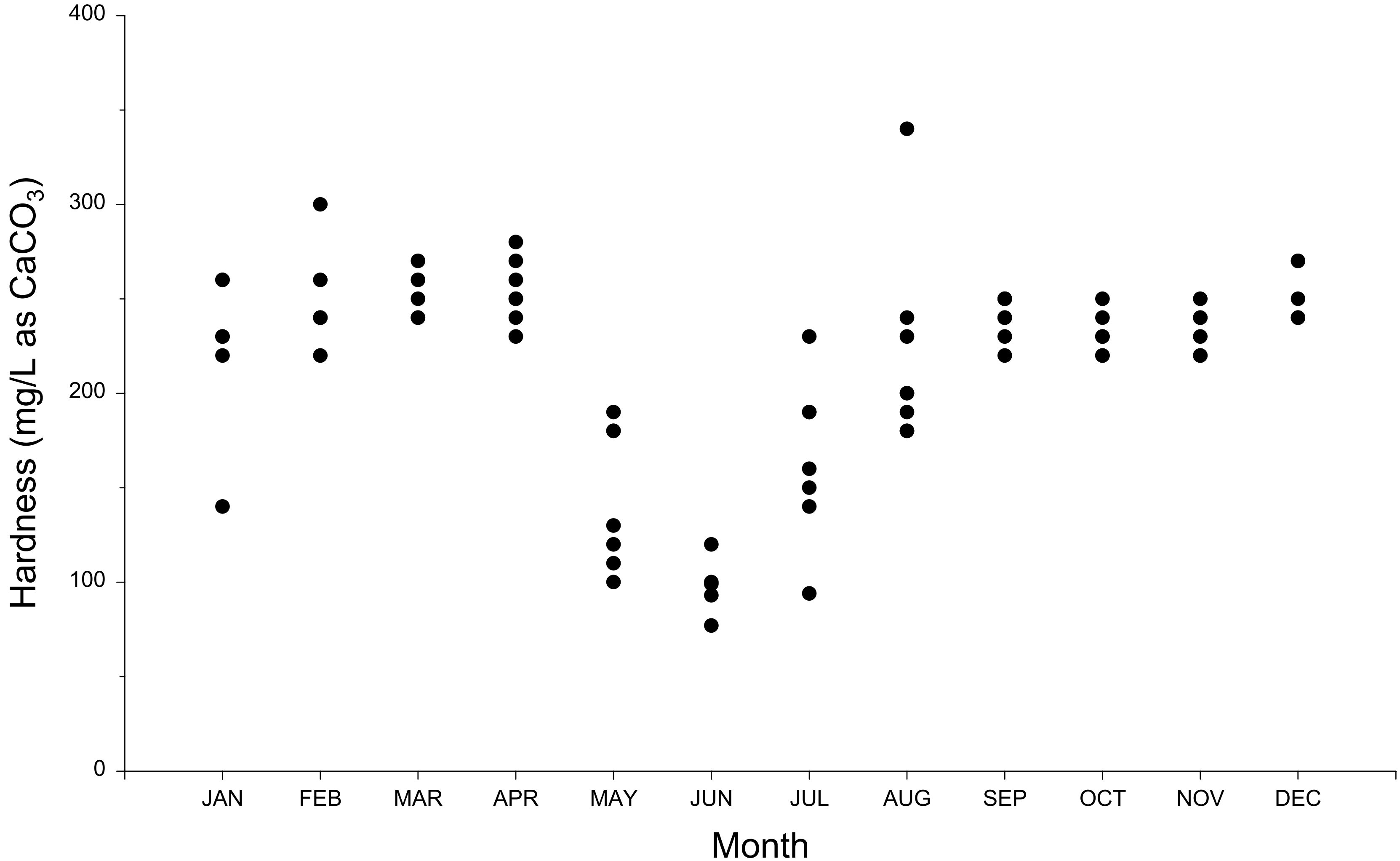

Figure A-7. Seasonal changes in hardness of surface water at the Tongue River Downstream site (USGS Site #06299980), from 1974 to 1983.

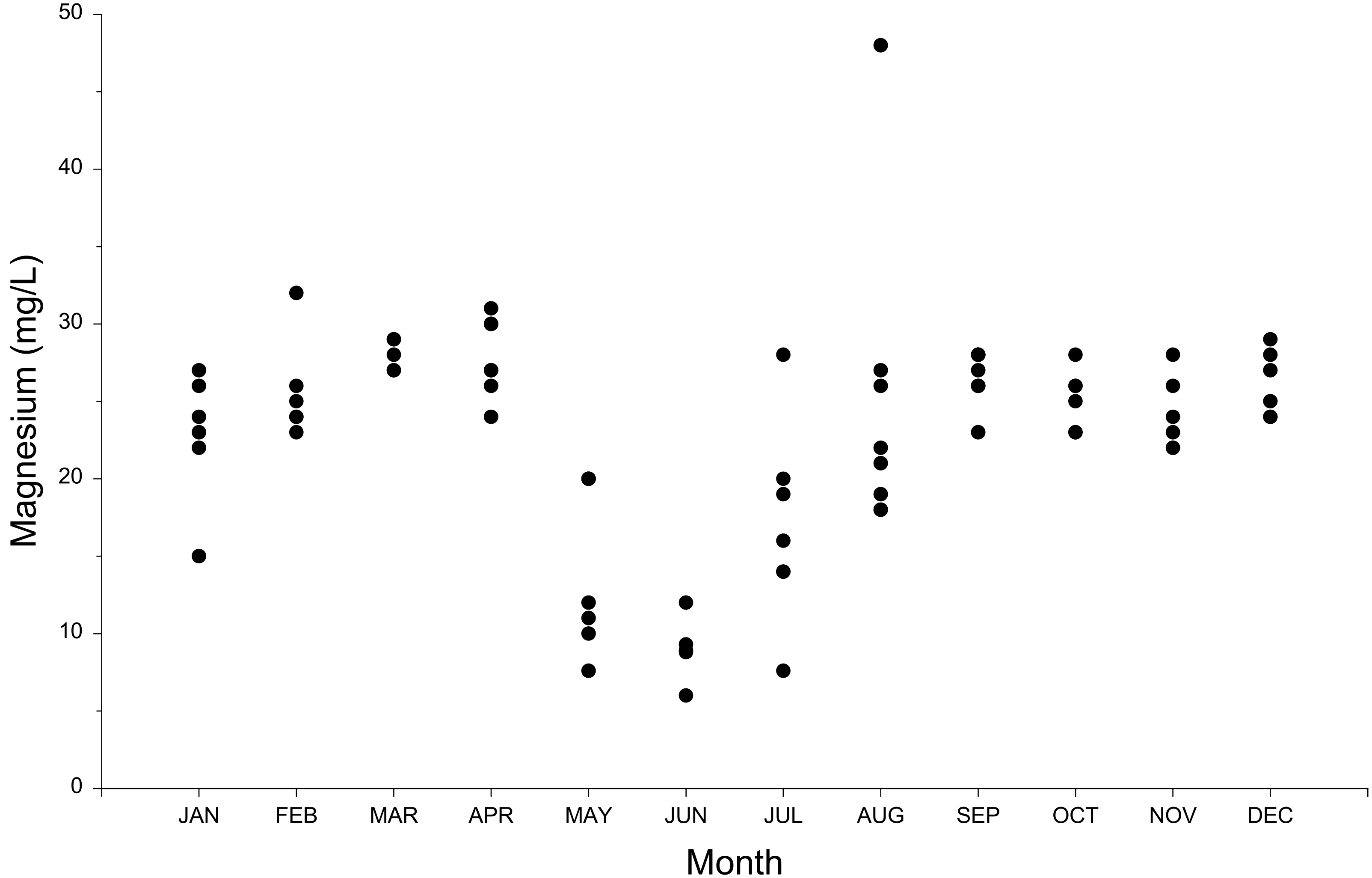

Figure A-8. Seasonal changes in magnesium concentration of surface water at the Tongue River Downstream site (USGS Site #06299980), from 1974 to 1983.

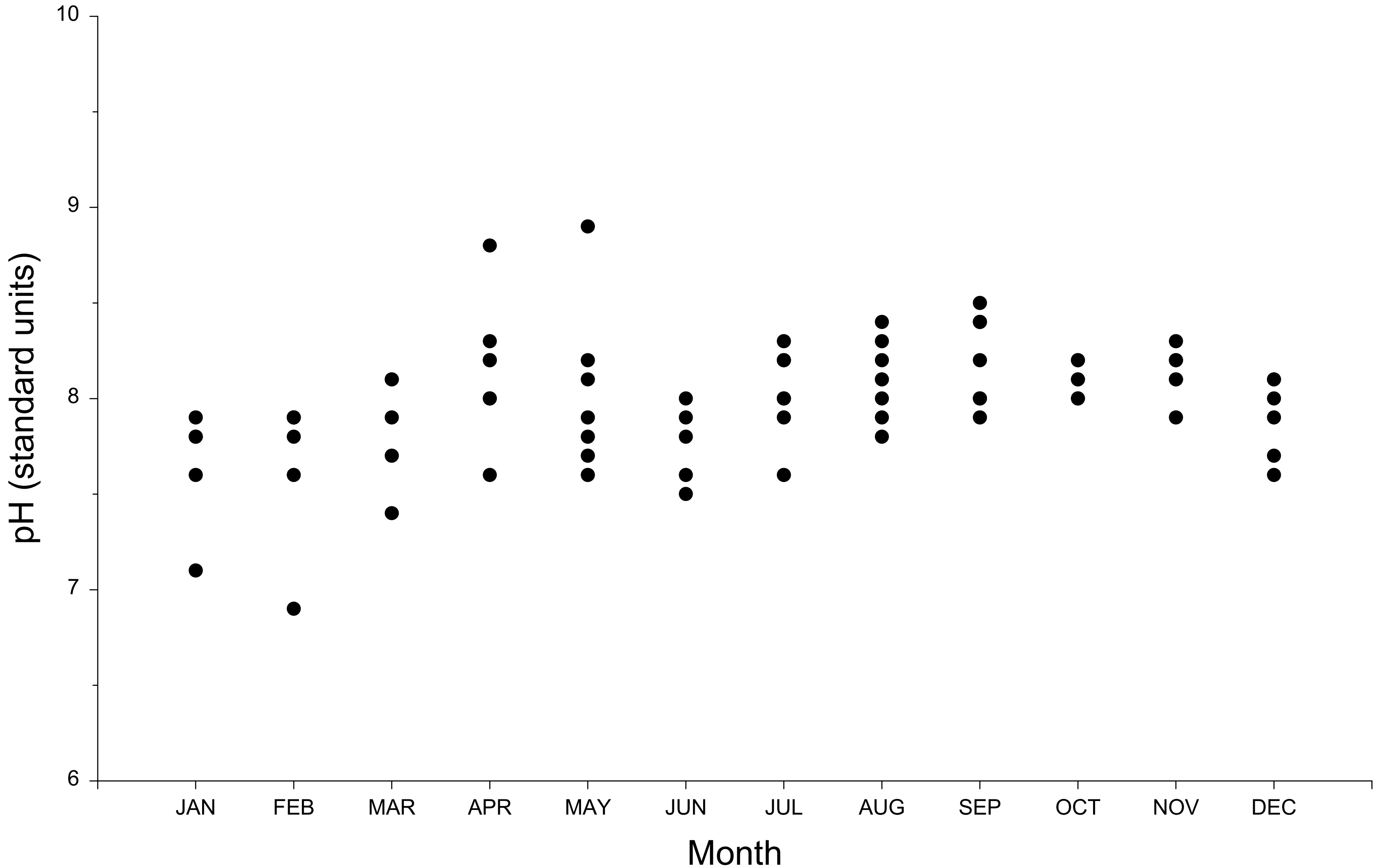

Figure A-9. Seasonal changes in pH of surface water at the Tongue River Downstream site (USGS Site #06299980), from 1974 to 1983.

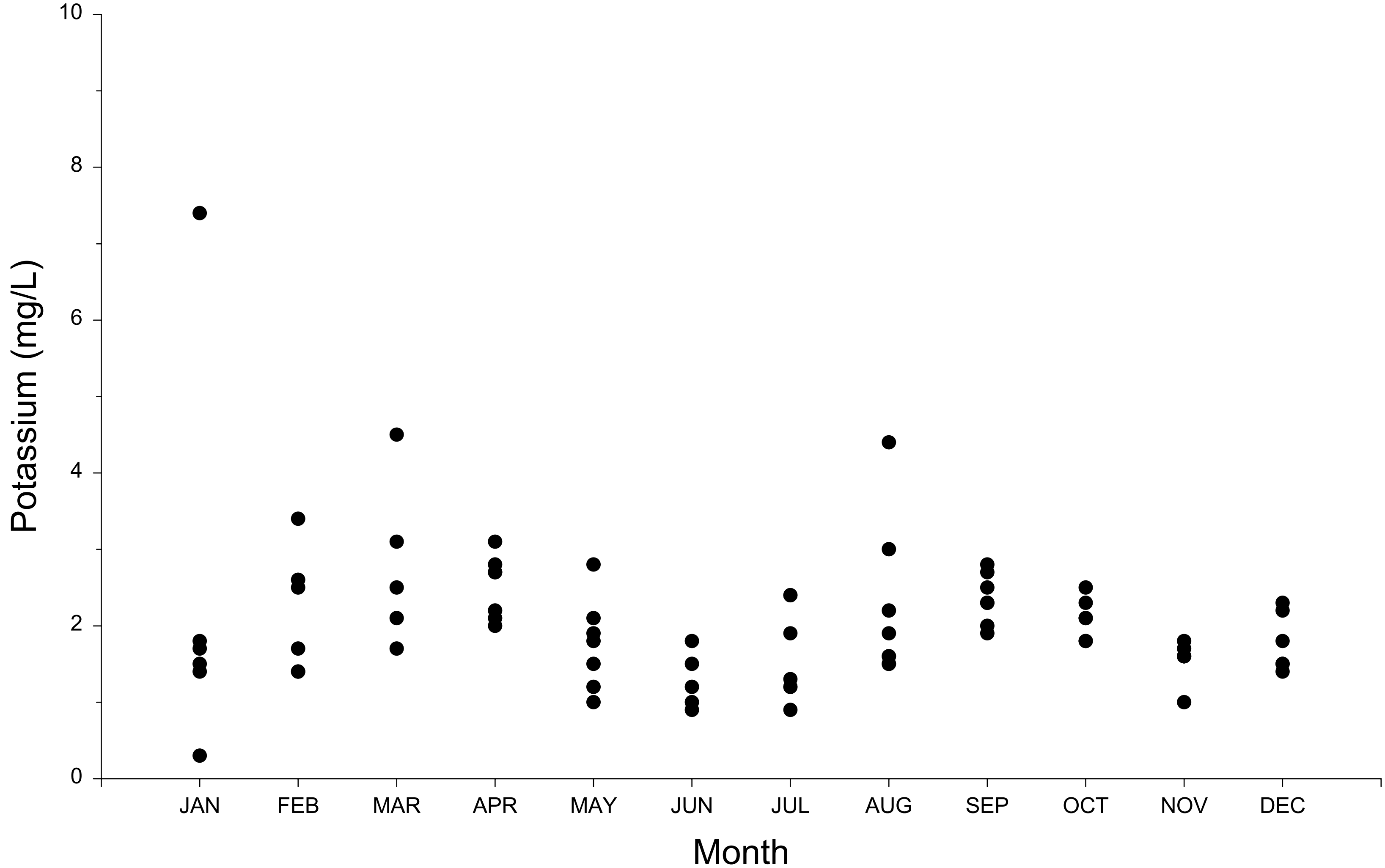

Figure A-10. Seasonal changes in potassium concentration of surface water at the Tongue River Downstream site (USGS Site #06299980), from 1974 to 1983.

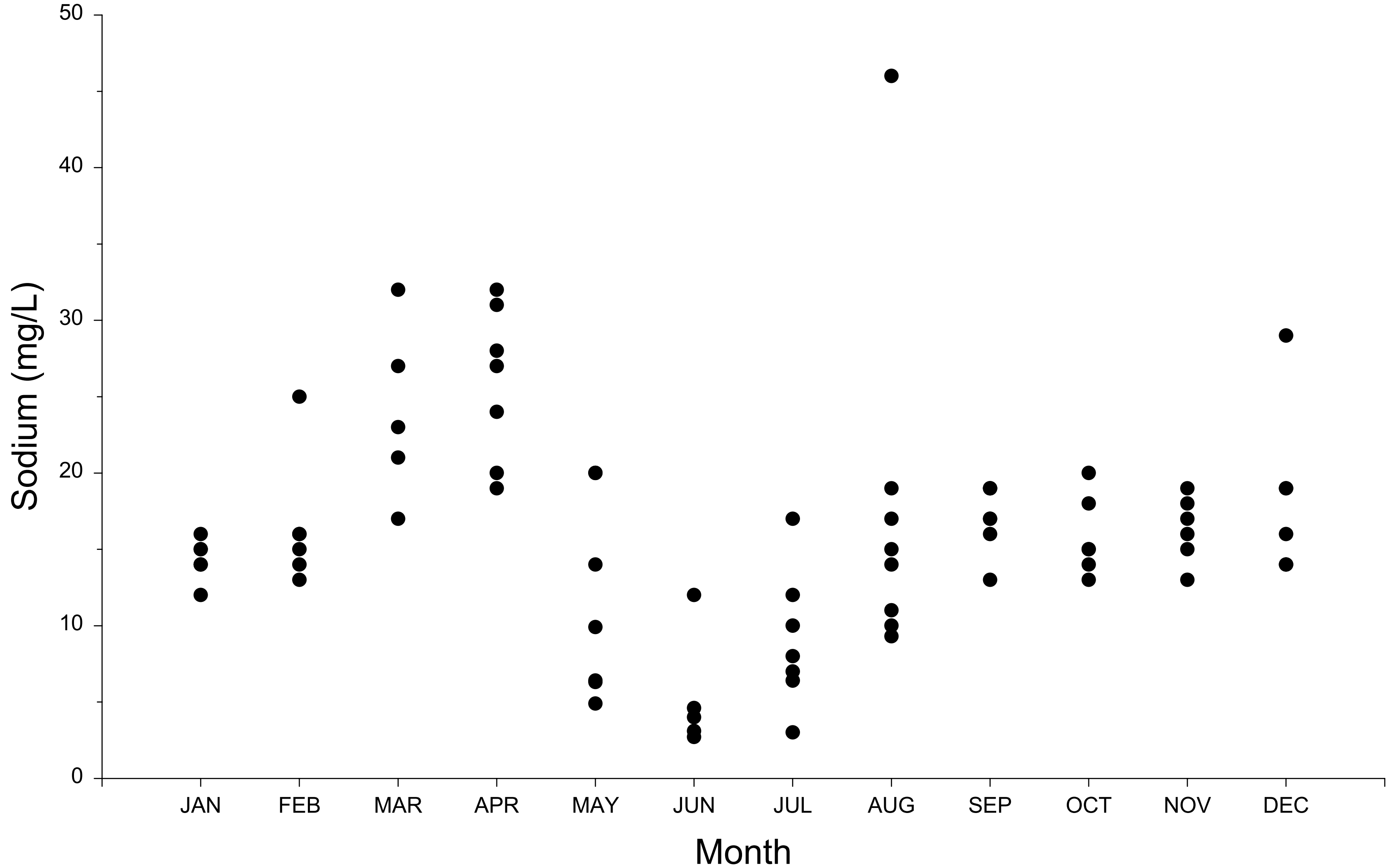

Figure A-11. Seasonal changes in sodium concentration of surface water at the Tongue River Downstream site (USGS Site #06299980), from 1974 to 1983.

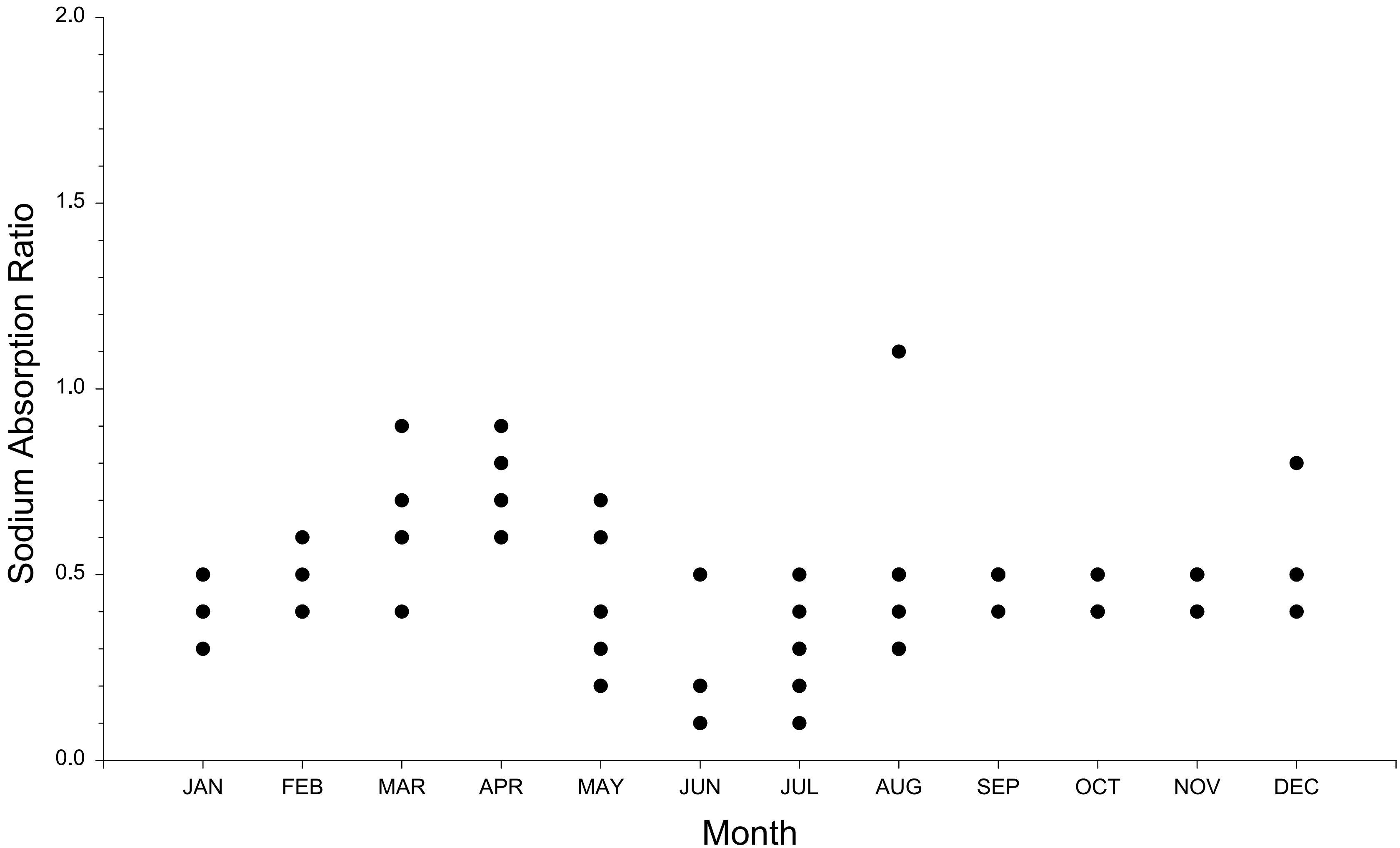

Figure A-12. Seasonal changes in sodium absorption ratio of surface water at the Tongue River Downstream site (USGS Site #06299980), from 1974 to 1983.

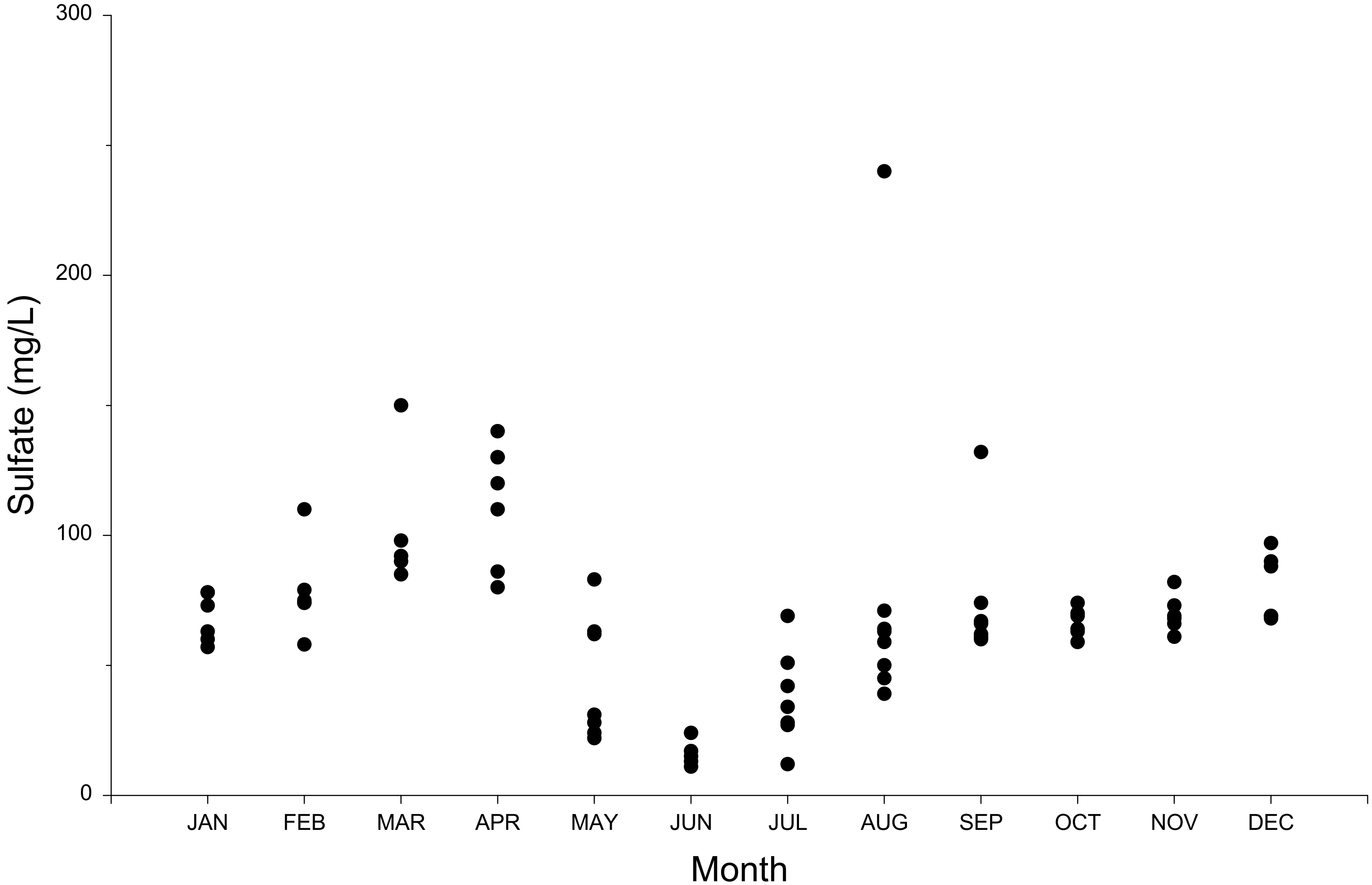

Figure A-13. Seasonal changes in sulfate concentration of surface water at the Tongue River Downstream site (USGS Site #06299980), from 1974 to 1983.

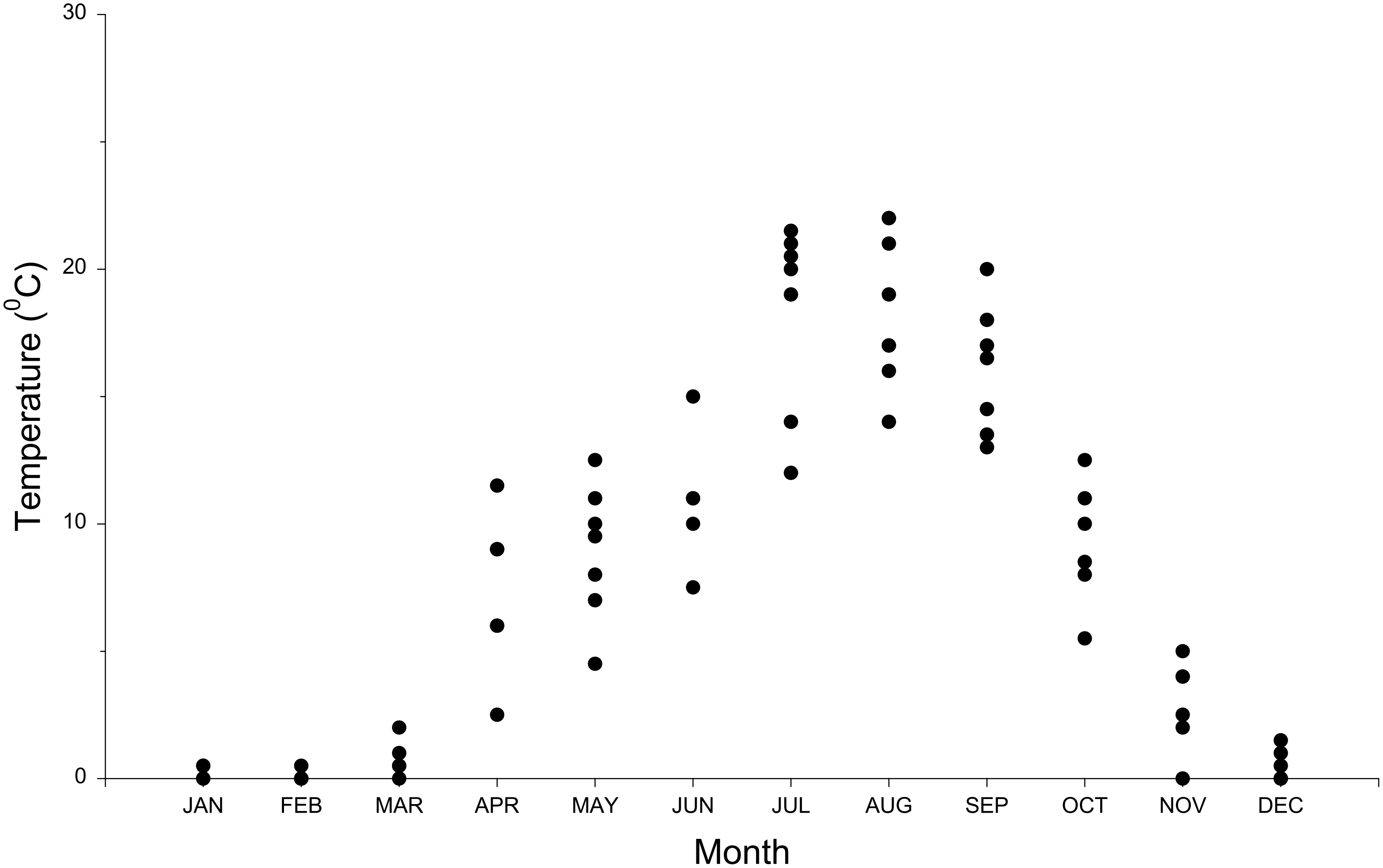

Figure A-14. Seasonal changes in temperature of surface water at the Tongue River Downstream site (USGS Site #06299980), from 1974 to 1983.

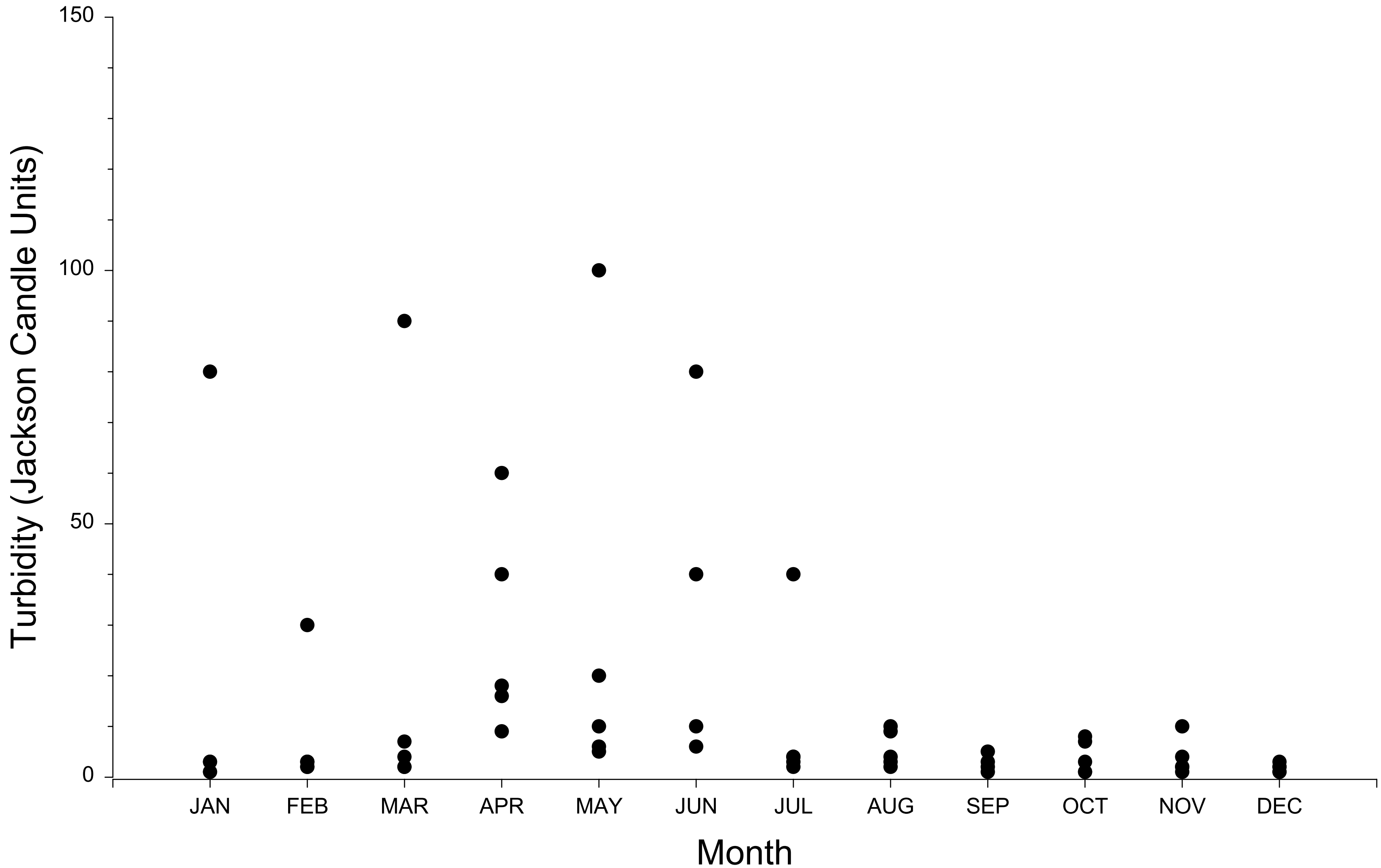

Figure A-15. Seasonal changes in turbidity of surface water at the Tongue River Downstream site (USGS Site #06299980), from 1974 to 1983.